5G: Adaptable Networks Enabled by Versatile Radio Access Technologies

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***Abstract*—The requirements and key areas for 5G are gradually becoming more apparent, and it is becoming clear that 5G will need to be able to deal with increased levels of diversity in both the requirements it must fulfil and the technologies that it uses to fulfil them. The diverse and demanding requirements for 5G necessitate a shift away from the rigid networks of previous generations, towards a more versatile and adaptable network. Essential to enabling this level of adaptability in 5G networks will be the new radio access technologies that are employed. In previous generations, the radio access network (RAN) was comprised of technologies and techniques that were tailored to satisfy the killer application of that era. In contrast, 5G will require versatile solutions that can be adapted to satisfy many different services and applications. The core network will also undergo fundamental changes, with increased levels of abstraction allowing for further reconfiguration of the network. The relationship between the RAN and core network will have a key role to play in managing and enabling adaptable networks. In this paper, we survey the choices and adaptability afforded by some of the radio access technologies being considered for 5G and explore how several system-level techniques, such as software-defined networking and cloud-RAN, can be utilised to enable and manage versatile 5G networks. Specifically, we focus on the relationship between new radio access technologies and emerging system-level techniques, examining how they may assist and complement each other. In this regard, we examine some tools such as virtualization and cognitive networks that can bridge this relationship. This paper is not intended to be a general survey on 5G, but rather a survey on how the requirements of flexibility and adaptability may be achieved in 5G through the coupling of versatile radio access technologies and emerging system-level techniques.**

***Keywords*—5G, adaptability, new waveforms, full duplex, cloud-RAN, massive-MIMO, software defined networks, virtualization, cognitive networks**

I. Introduction

As the requirements and research directions for 5G are slowly beginning to crystallize, it is becoming apparent that 5G will have a distinctly different flavour than previous generations of mobile network standards. This difference can be largely attributed to the core ideas of versatility and adaptability, which will need to be prevalent throughout the entire network. In this paper, we explore how 5G will be characterised by greater versatility and adaptability of radio access technologies (RAT) and system-level architectures that cooperate with one another to cater to diverse service requirements.

In previous generation increments, the primary focus was on increased data rates. Although the need for increased data rates retains its relevance as we progress towards 5G, the requirements for 5G are far more multifaceted than anything before [1]–[3]. New services such as high definition video, traffic safety, e-Health, and automated industry have diverse and often conflicting needs. The myriad of services to be supported can be categorized into three primary areas, which are currently the focus of 3GPP:

1) enhanced Mobile Broadband,
2) massive Machine Type Communications,
3) ultra-reliable low latency communications.

Each area presents different requirements to the network in terms of data-rate, latency, reliability, and energy efficiency. 5G networks may need to be able to handle a 1000x increase in current traffic volumes, provide a 100x increase in the edge data rate, support a latency in the region of 1ms, provide ultra-high reliability and availability, all the while reducing or at least maintaining current energy consumption and costs.

It is difficult to design a network capable of fulfilling all of these service requirements simultaneously. Therefore, unlike previous generations, which were primarily defined by their approach to the air interface and multiple access scheme (i.e., UMTS/WCDMA and LTE/OFDMA), 5G will be distinguished by the unprecedented level of flexibility present throughout the entire network. Designed in a versatile manner to adapt to the requirements of a diverse range of services, 5G will need to improve on the flexibility afforded by 4G, moving towards a more encompassing solution that is ubiquitous throughout the entire network. We use the word versatile to define the high level of malleability and adaptability that 5G must possess. A versatile 5G network is a full network solution in which different network layers, from the radio access technologies to the system-level techniques, may adapt in a harmonious fashion to suit the needs of a particular service.

The new range of radio access technologies being considered for 5G, such as in-band full duplex (IBFD), new waveforms, millimeter wave (mmWave), and massive-MIMO (M-MIMO), demonstrate clear heterogeneity in their capabilities and strengths. MmWave, for example, presents new challenges such as extreme sensitivity to blockages, but offers remarkable data rates when used in the right environments.

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As another example, in-band full duplex introduces new types of interference into the network, yet may potentially double the spectral efficiency depending on the interference profile of the cell. New technologies do not always equate to better performance in every situation, but rather introduce more choice and versatility.

However, while important, changes in the radio access technologies alone will not be enough to support the wide range of services envisioned. Hence, 5G will also likely see the emergence of new system-level techniques and architectures aimed at increasing capacity and reducing the overhead associated with managing the network, such as small cells, cloud-RAN, and software defined networking (SDN). In the context of adaptable networks, these techniques are doubly relevant. Firstly, they bring inherent flexibility to the network through the increased level of abstraction that they introduce. Second, they have an important part to play in the creation and management of versatile networks.

In this paper, we survey some of the radio access technologies and system-level architectures that are critical to achieve the level of versatility required in 5G. Specifically, we focus on the interplay between the new radio access technologies being considered and the emerging system-level techniques for 5G, in order to establish how they may assist one another towards the goal of increased versatility and adaptability. This relationship is of key importance if the vision of 5G as a highly adaptable network is to be realised. In Section IV, we explore some promising approaches for enabling this relationship, as well as the associated future research directions and challenges.

This paper is not a general survey of 5G: such works already exist in the literature [4]–[7]. Nor is the purpose of this paper to provide a survey of various key radio access technologies and system-level techniques for 5G; there are many surveys that individually deal with each of the topics we discuss in far more detail (listed in Table I for convenience), and we will refer the interested reader to these where relevant. Instead, the key contribution of this paper is the study of ways in which new radio access technologies and emerging system-level techniques may assist and complement each other to enable the creation of versatile networks that are able to adapt to various service requirements, as captured in Fig. 1.

The main contributions of the paper are as follows:

1) we promote the vision of 5G as a highly versatile and reconfigurable network, capable of adapting to many different service requirements.
2) we identify the relevant research questions that are required to bring about this vision.
3) we survey the technologies and tools that will be instrumental in realising this vision of flexible networks, specifically focusing on the relationship between new versatile radio access technologies and emerging system-level techniques.

The paper is structured as follows: Section II focuses on new radio access technologies, surveying the choices and options that may be presented by the future 5G PHY and MAC layers. Section III takes a system-level view of 5G, examining the contributions that new techniques can offer to an adaptable network in terms of both performance and management. Section

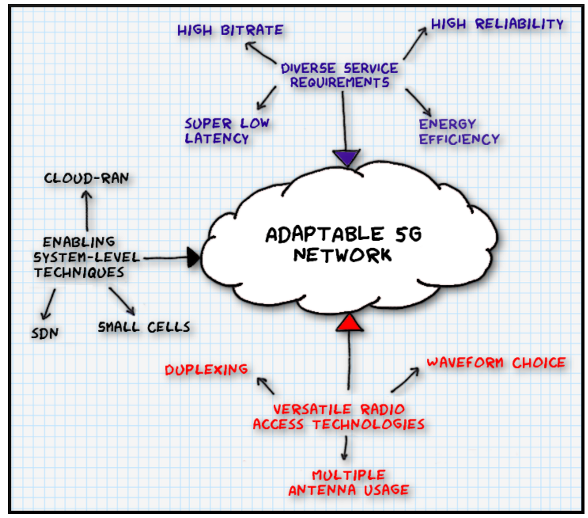

Fig. 1. Versatile radio access technologies and emerging system-level techniques combining to form a 5G network capable of adapting to various service requirements.

TABLE I. TABLE OF DETAILED SURVEYS ON TOPICS COVERED IN THIS PAPER.

Survey	Topic	Group description
[4]–[7]	General surveys of 5G	Provides broad overview of select topics and technologies that are central to the 5G discussion, and reviews current work in each area.
[8]–[12]	In-band full duplex	Reviews developments, challenges, and opportunities related to different aspects of in-band full duplex such as MAC design, antenna design, and application to relaying.
[13], [14]	Spatial modulation	Focuses specifically on the area of spatial modulation, and discusses developments in this area.
[15]–[21]	New waveforms	Explores the various waveform contenders for 5G, discussing the properties, implications and merits of various options, as well as offering comparisons of relative performance.
[22]–[24]	Cognitive radio and spectrum sharing	Surveys developments in cognitive radio and spectrum sharing with a view towards future networks.
[25]	Network virtualization	Provides survey of some of the work that has already been undertaken to achieve wireless network virtualization, and discusses the research issues and challenges that remain.
[26]–[30]	Software defined networking	Focuses on the area of software defined networking, providing a general overview of work in the field, as well as more specific surveys on Openflow, wireless SDN, and virtualization hypervisors.
[31]	Cloud-RAN	Presents the state-of-the-art on cloud-RAN, and discusses both the advantages and challenges associated with it.
[32]–[34]	Millimetre wave	Explores the possibilities offered by millimeter wave communications and surveys initial works in this area, focusing on its feasibility for 5G, as well as the challenges still to be solved.

TABLE II. EXPANDED FORM OF ACRONYMS USED IN THIS PAPER

Acronym	Expanded Form	Acronym	Expanded Form
3GPP	3rd Generation Partnership Project	AMC	Adaptive Modulation and Coding
AP	Access Point	API	Application Program Interface
ASM	Adaptive Spatial Modulation	ATA	Autonomous Timing Advance
BBU	Baseband Processing Unit	BS	Base Station
CAPEX	Capital Expenditure	CAPWAP	Control and Provisioning of Wireless Access Points
CoMP	Coordinated Multipoint	CP	Cyclic Prefix
CPRI	Common Public Radio Interface	CSI	Channel State Information
D2D	Device-to-Device	DAS	Distributed Antenna System
DSA	Dynamic Spectrum Access	eNB	eNodeB
FBMC	Filter Bank Multicarrier	FDD	Frequency-division Duplexing
FFT	Fast Fourier Transform	FMT	Filtered Multi-Tone
f-OFDM	filtered Orthogonal Frequency Division Multiplexing	GAA	General Authorized Access
GFDM	Generalised Frequency Division Multiplexing	HD	Half Duplex
IBFD	In-band Full Duplex	ICI	Inter-Carrier Interference
ICIC	Inter-Cell Interference Coordination	IFFT	Inverse Fast Fourier Transform
InP	Infrastructure Provider	ISI	Inter-Symbol Interference
ISM	Industrial, Scientific and Medical	JR	Joint Reception
JT	Joint Transmission	LAA-LTE	Licensed Assisted Access-LTE
LBT	Listen Before Talk	LSA	Licensed Shared Access
LTE	Long Term Evolution	LTE-U	Long Term Evolution Unlicensed
LVAP	Light Virtual Access Point	MIMO	Multiple Input Multiple Output
mmWave	Millimetre Wave	M-MIMO	Massive-MIMO
MNO	Mobile Network Operator	MTC	Machine Type Communication
MVNO	Mobile Virtual Network Operator	MVNP	Mobile Virtual Network Provider
NOMA	Non-Orthogonal Multiple Access	OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access	OPEX	Operational Expenditure
PMI	Precoding Matrix Indicator	PSD	Power Spectral Density
PU	Primary User	QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience	RA	Resource Allocation
RAN	Radio Access Network	RAT	Radio Access Technology
RANaaS	Radio Access Network as a Service	RoF	Radio over Fibre
RRH	Remote Radio Head	SAN	Software Adjustable Network
SAS	Spectrum Access System	SC-FDMA	Single Carrier- Frequency Division Multiple Access
SCM	Single Carrier Modulation	SCMA	Sparse Code Multiple Access
SDAI	Software Defined Air Interface	SDN	Software Defined Networking
SDR	Software Defined Radio	SDW	Software Defined Waveform
SDWN	Software Defined Wireless network	SI	Self-Interference
SIC	Self-Interference Cancellation	SM	Spatial Modulation
SoDeMA	Software Defined Multiple Access	SP	Service Provider
SU	Secondary User	TDD	Time-division Duplexing
TTI	Transmission Time Interval	UE	User Equipment
UFMC	Universal Filtered Multicarrier	UMTS	Universal Mobile Telecommunications System
U-NII	Unlicensed National Information Infrastructure	VAP	Virtual Access Point
WCDMA	Wide-Band Code-Division Multiple Access	WDTX	WiFi Datapath Transmission
WLAN	Wireless Local Area Network		

IV examines two options that offer the potential to bridge the complementary relationship between system-level techniques and radio access technologies, as well as the associated issues, challenges, and future research directions. Finally, Section V concludes the paper.

A list of the acronyms used in this paper is provided in Table II.

II. Radio Access Technologies in 5G

5G has the potential to offer an unprecedented level of flexibility in the radio access level technologies it employs. With so many diverse requirements to satisfy, these PHY technologies provide the basic building blocks from which to construct versatile networks that can be adapted according to the services to be supported. 5G will be characterized by both the specific technologies it adopts, and the ability it offers to configure these technologies to suit particular use-cases.

In this section, we focus on three core areas that will form the main ingredients of any 5G PHY layer: duplexing, multiple antenna use, and waveforms.

A. Duplexing

The notion that radios cannot send and receive simultaneously using the same spectral resources is based on the fact that the locally generated transmitted signal can be several orders of magnitude stronger than the signal to be received, essentially drowning it out and resulting in severe crosstalk between the transmitter and receiver. However, given recent developments in self-interference cancellation, in-band full duplex (IBFD) is now feasible for low-power, short-range systems such as small cells [35] and device-to-device (D2D) communication [36], which are expected to play an important role in 5G. The main benefit that in-band full duplex offers is the potential of doubled spectral efficiency and capacity.

Self-interference (SI) represents the biggest challenge in achieving in-band full duplex. Different self-interference cancellation (SIC) schemes vary in their cancellation capabilities, greatly affecting the performance of IBFD. In order to render self-interference negligible, it is necessary to reduce it to the same level as the noise floor. In Wi-Fi systems, with 20dBm average transmit power and a noise floor of around -90dBm,

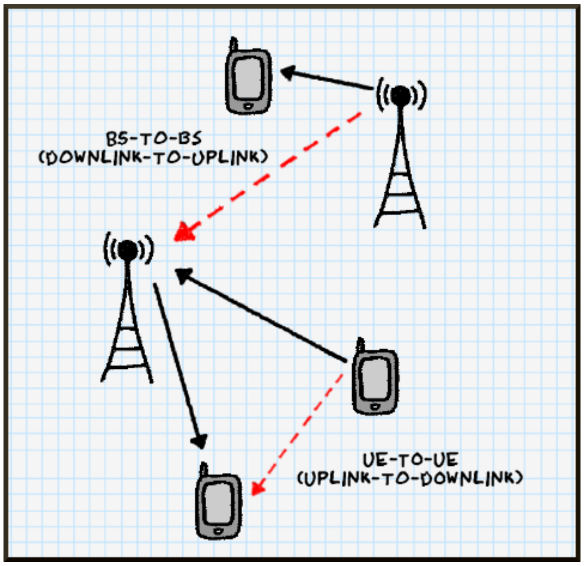

Fig. 2. In-band full duplex introduces two new types of interference into systems, namely uplink-to-downlink and downlink-to-uplink.

110dB of cancellation is required. This figure is quoted from [37], which presents the design and implementation of an in-band full duplex radio that is capable of providing this 110dB of cancellation. [11] calculates that a reliable communication link in a small cell would require a 104dB reduction in SI, and provides a table detailing the cancellation achieved by current SIC schemes in the literature. Given the larger transmit powers and distances involved, even greater cancellation must be achieved if IBFD is to become a viable technology for full-scale cellular networks.

It is clear that the performance of in-band full duplex is affected by many factors such as link distance, transmit power, and SIC capabilities. In addition, IBFD introduces two new types of interference to the cellular network [38], namely inter-cell base station (BS)-BS and intra-cell user equipment (UE)-UE, as illustrated in Fig. 2. As a result, the promise of doubled capacity using IBFD often falls short. [39] employs stochastic geometry to analyse a multi-cell OFDMA setting and reports that while double capacity is not reached, capacity is still greatly increased. [40] reports similar findings for indoor scenarios, reporting $30\% - 40\%$ gains.

Increased spectral efficiency is not the only benefit that IBFD can offer. IBFD can be used to reduce control plane latency, since feedback information such as channel state information (CSI) and acknowledgements can be received during data transmission. In addition, advances in SIC enable faster collision detection since a transmitting device can simultaneously listen for collisions. This is of particular interest for contention based protocols or dynamic spectrum access.

IBFD is an exciting technology with great potential; however, understanding when and how to use it is critical to its successful integration. In this section, we survey the many choices and options presented by IBFD, and explore the flexibility that it introduces into the network.

We refer the interested reader to [8] for more details on in-band full duplex. [9] discusses the design of medium access control protocols for IBFD systems. For more details on interference cancellation algorithms and the low-level details of IBFD radios, we refer the reader to [10], [11]. In the remainder of this section, we explore some of the choice and flexibility that is introduced into the network with the advent of IBFD and SIC.

Hybrid Duplexing: We have already highlighted that IBFD performance depends on numerous factors such as SIC capabilities, pathloss between devices, and transmit power. In many cases, the new types of interference introduced into the network prevent the promise of potentially doubled capacity from being realised. In some cases, strong interference may even render IBFD less favourable than conventional duplexing[1] techniques. [41] derives the conditions for in-band full duplex gain in a single cell scenario and proposes a hybrid scheduler which decides whether to schedule both an uplink and downlink UE in a resource block, or whether to default to traditional half duplex (HD)[2] operation. This leads to the concept of hybrid duplexing, in which the duplexing scheme is chosen depending on current conditions.

With regard to choosing a duplexing mode, four choices reveal themselves:

1) Time-division duplexing (TDD);
2) Frequency-division duplexing (FDD);
3) In-band full duplex (IBFD);
4) Hybrid duplexing.

Hybrid duplexing involves a controller which, based on a set of parameters of concern, decides when to exploit IBFD communications and defaults to a conventional duplexing technique if conditions are not favourable.

- Hybrid duplexing for cellular access: The potential to boost spectral efficiency and cell capacity makes IBFD attractive for cellular access. Most of the literature focusing on cellular access considers the scenario whereby the base station operates in IBFD mode while legacy UE terminals are only HD capable [39], [42]. [43] identifies the main challenge in such a situation to be the optimal scheduling of UEs for uplink and downlink in the same frequency resource. [44] notes that the use of pure IBFD may not be optimal in every situation due to the effects of interference, and considers the use of a centralized adaptive scheduler in a scenario consisting of a IBFD base station and half duplex UEs. The scheduler may decide to schedule either one uplink, one downlink, or a pair of uplink and downlink UEs in a resource block depending on the interference. The objective is to maximise the joint uplink and downlink utility of the system with

[1] Conventional duplexing refers to the use of either half duplex techniques, where simultaneous transmission and reception is not possible, or out-of-band full duplex, where simultaneous transmission and reception is only possible using different frequency bands.

[2] To be precise, half duplex refers only to techniques that may either transmit or receive in a certain time slot, but not both. However, in keeping with the literature on hybrid duplexing, we use the term half duplex instead of conventional duplexing to mean either time-division duplexing (TDD) or frequency-division duplexing (FDD).

proportional fairness, assuming global system knowledge. [45] proposes a hybrid scheduler based on a distributed approach that is capable of performing almost as well as a centralized approach. [46] proposes a hybrid scheduler that switches between in-band full duplex and half duplex modes depending on the self-interference cancellation values.

- Hybrid duplexing for device-to-device communication: D2D allows nearby devices to establish direct links, negating the need to make a round trip via the base station and hence increasing the overall system throughput. The application of IBFD transmission in D2D communications appears to be a sensible fit, as the distance between paired devices is typically short, thereby increasing the ratio between the received signal strength and self-interference strength. Most of the current research into the coexistence of D2D and IBFD focuses on using IBFD communications between device pairs to boost spectral efficiency [47]–[49]. This is achieved at the cost of increasingly complicated interference channels to be considered. This scenario also requires devices to be IBFD capable. D2D involves a delicate balance between increasing the overall system throughput and keeping the interference introduced by direct transmission between pairs to a minimum. Protecting existing cellular users is a primary concern in D2D. Hybrid duplexing may offer benefits in an IBFD D2D scenario and still requires investigation. This may take the form of BS assisted hybrid scheduling, or each individual D2D pair may autonomously decide for themselves. The decision between using full or half duplex may be influenced by a number of factors related to the interference profile of the cell, including self-interference, D2D-to-UE interference, and UE-to-D2D interference.
- Hybrid duplexing for relaying: Relaying is another potential application of IBFD that is attracting plentiful attention due to the possibility of increasing the data-rate by transmitting and receiving using the same frequency resources. The concept of hybrid duplexing is again relevant in this scenario, as highlighted by [50], which considers hybrid IBFD/HD relaying with opportunistic mode selection and demonstrates the performance gain offered by such a system over a system confined to a single duplexing scheme. [51] proposes an adaptive IBFD/HD relaying scheme consisting of three modes: orthogonal reception, orthogonal transmission, or simultaneous reception and transmission at the relay. [52] demonstrates that hybrid transmission mode for relays can achieve better performance than just using in-band full duplex or half duplex transmission mode alone. The subject of resource allocation in virtualized IBFD relays is discussed in [53], [54], considering spectrum, base stations, and relays as virtual resources.
- Hybrid duplexing for self-backhauling: Self-backhauling refers to a technique whereby a base station uses part of its available spectral resources for wireless backhauling. Traditionally macro-cells have been backhauled using a form of guided transmission such as optical fibre. While this has proved to be effective, wireless backhaul provides a cheaper alternative for the huge numbers of low-power, low-cost nodes that will be deployed in 5G networks. [55] provides an overview of the techniques and challenges associated with backhauling small-cells in 5G. The authors characterize the cellular region in which the use of in-band self-backhauling limits the downlink capacity of the cell, and suggests the use of IBFD as a way to improve performance.

  [56] highlights the importance of backhaul-aware radio resource management. This is especially important in an IBFD-capable small-cell that uses spectral resources simultaneously for both access and backhaul. In relation to IBFD cellular access, we already drew special attention to the possibility of a hybrid scheduler that decides whether to operate in IBFD mode or default to HD mode. This notion of hybrid duplexing for cellular access is even more prevalent in a scenario involving in-band backhauling. Furthermore, this concept can be extended to the backhaul case as explored in [57], in which the authors demonstrate the usefulness of adaptive IBFD/HD self-backhauling over IBFD self-backhauling alone. In adaptive IBFD/HD self-backhauling, the duplexing scheme is dynamically changed according to the current interference conditions.
- Hybrid duplexing for dynamic spectrum access (DSA): DSA has been heralded as a promising technique to deal with the perceived spectrum shortage at microwave frequencies, allowing unlicensed secondary users (SU) to avail of licensed bands according to a strict set of rules. The rules defining how and when an SU can use licensed spectrum are designed with a strong emphasis on protecting the incumbent. Typically in a cognitive radio, the SU will perform spectrum sensing at the beginning of each time slot and begin transmitting if the received power is below some predefined threshold. Two problems are evident with this approach. Firstly, multiple SUs might opportunistically attempt to access the medium, resulting in secondary collisions. Secondly, the primary user (PU) may become active at any time and the SU cannot detect this while it is transmitting. SIC has been proposed to enhance the performance of cognitive radios, reducing the number of SU collisions and offering greater protection to the incumbent, as it allows SUs to perform spectrum sensing while simultaneously transmitting [58]–[61]. [62], [63] consider an adaptive transmission-reception-sensing strategy in which the cognitive radio may utilize the benefits of IBFD in two ways:

  1) Simultaneous transmission-and-sensing mode to improve detection probability.
  2) Simultaneous transmission-and-reception mode to improve throughput.

  A spectrum awareness/efficiency trade-off arises from the adaptive switching strategy, with a threshold between the two depending on the SU's beliefs about PU activity. If an SU has a strong belief regarding PU idleness in a certain channel, the SU should operate in simultaneous transmission-and-reception mode. If this belief decreases, the SU should switch to simultaneous transmission-and-sensing mode in order to constantly monitor PU activity while transmitting. Being able to predict PU activity, therefore, has a great influence on which mode is selected, and hence on the overall performance of the system. Spectrum occupancy models are beneficial in this regard, and can be used to make predictions on PU activity based on measurement campaigns. Several different spectrum occupancy models are surveyed in [64], [65]. [66] states the importance of conducting occupancy measures over a specific area rather than a single location, and surveys measurement campaigns and associated interference maps. Interference maps characterize spectrum occupancy over an area of interest in a certain frequency band. Hence, spectrum occupancy models for a certain area may influence the mode in which a cognitive radio with IBFD capabilities operates.

SIC enabling flexible use of spectrum One of the greatest advantages that SIC introduces in the context of enabling versatile networks is the potential for network operators to make use of their licensed spectrum as they see fit. [67] highlights some of the possible ways that SIC can be utilized including any-division duplexing and spectrum virtualization.

- *Spectrum virtualization:* SIC's ability to isolate any pairs of transmit and receive frequencies allows it to act as a software controlled duplexer. IBFD relates to the case whereby the uplink and downlink channels are completely overlapped. SIC allows any two channels to be paired, including partially overlapped channels. A software defined duplexer would simplify the effort associated with supporting fragmented spectrum.
- *Any-division duplexing:* SIC can enhance FDD with increased opportunities to be configurable, allowing it to exploit carrier aggregation. For example, similar to the concept of spectrum virtualization, SIC enables partially overlapping channels to be paired for uplink and downlink in FDD. This is complemented by IBFD, which allows completely overlapping bands to be paired. The different duplexing possibilities are illustrated in Fig. 3.

The introduction of IBFD communication, and more generally the concepts of any-division duplexing and software controlled duplexing, will have implications on the manner in which spectrum is auctioned to the highest bidder and assigned. In [68], the authors highlight the inefficiencies in current practices for allocating spectrum to operators and call for the removal of restrictions on spectrum. One of the restrictions highlighted in the paper, and which is most relevant in this case, is the pre-designation of spectrum as either FDD or TDD prior to allocation. Spectrum to be auctioned is stipulated to either be FDD or TDD irrespective of the services that it will be used to support or expected traffic patterns. Clearly this imposes severe difficulties for the introduction of any-division duplexing.

Several works in the literature have proposed alternative auction formats such as the combinatorial clock auction [69]–[71], specifically in the context of cognitive radios. One of the advantages of combinatorial clock auctions over conventional auctions is that it allows bidders to group combinations of discrete items into packages. This reduces the financial exposure of bidders as they either purchase the entire package or nothing at all, as opposed to being awarded an inferior subset. [72] proposes further flexibility through more expressive bids that allow bidders to make customized requests, as opposed to limiting them to a set of discrete options consisting of large predefined blocks of spectrum. Through expressive bids, requests for variable paired FDD and unpaired TDD spectrum can be made, including asymmetric FDD pairings. The advent of new concepts in duplexing such as in-band full duplex and any-division duplexing requires further work in the area of spectrum auctions in order to allow network operators to bid for spectrum irrespective of the duplexing scheme they wish to implement.

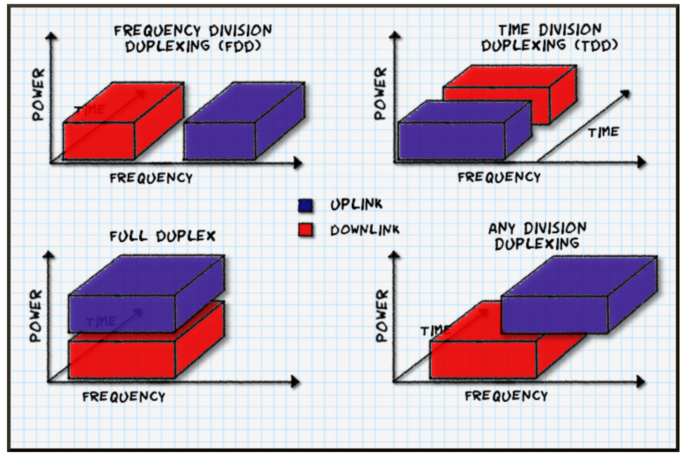

Fig. 3. Duplexing has always been either frequency division duplexing (FDD) or time division duplexing (TDD). Improvements in SIC allows both full and partial overlap of uplink and downlink bands.

B. Multiple Antenna Use

The ability to utilise multiple antennas comes with inherent choice in how to use them, which directly dictates the resulting benefits. 5G architectures are likely to consist of dense small cell deployments underlaying Massive-MIMO (M-MIMO) enabled macro-cells, massively deployed remote radio heads (RRH) in cloud-RAN, and distributed antenna systems (DAS) (note that these are not mutually exclusive).

Although the benefits of MIMO are being realised in current 4G systems with base stations equipped with up to eight antennas, 5G will take this idea a step further, or orders of magnitude steps further, with the introduction of Massive-MIMO. M-MIMO plays a prominent role in many of the 5G visions portrayed in the literature [1], [6], [73], and is commonly mentioned as one of the most promising enabling technologies to meet the demanding requirements of future networks. In an M-MIMO system, the base station is equipped with a large antenna array, often in the order of hundreds of individual antennas. The addition of massive numbers of antennas introduces increased degrees of freedom in the propagation environment which can be exploited to provide gains in throughput and/or robustness. Fig. 4 illustrates the different benefits that MIMO can afford.

M-MIMO has the potential to drastically alter resource allocation in cellular networks by simplifying the medium access control (MAC) layer, mitigating the need for complex scheduling algorithms as multiple users can now be scheduled simultaneously using the same time-frequency resource [73]. In addition, as the number of channel observations grows, the law of large numbers comes into play and channel responses are averaged out thanks to spatial diversity. This *hardening* of the channel renders frequency domain scheduling redundant and alleviates most physical layer control signalling as each subcarrier possesses essentially the same channel gain [74].

The availability of multiple antennas offers many potential advantages to network operators, dependent on how they wish to utilise the antenna resources at their disposal. Capacity, data-rate, and reliability gains are all possible depending on the multiple antenna technique in use. Depending on the service being considered, a network operator may decide to employ techniques including MIMO, spatial modulation, and coordinated multipoint (CoMP). Each technique offers varying advantages, as well as different levels of flexibility and customizability. In this subsection, we explore the flexibility and choices associated with multiple antenna use and how it can aid network operators in the creation of versatile networks.

Diversity/Multiplexing choices Multiple antenna technologies such as MIMO can be used in two broad formats: diversity for increased reliability, or multiplexing for increased capacity. The decision whether to utilise the multiplexing or diversity gains of MIMO depends on the particular propagation environment, and the priorities of the network operator, who may value reliability over capacity or vice-versa.

1) *Diversity/robustness:* Multiple copies of the signal are received over independently fading channels, increasing the probability that the receiver will be able to detect the transmitted signal without error and, hence, improving reliability.
2) *Spatial multiplexing/throughput:* Spatial multiplexing aims to increase the capacity of a system by sending different signals over the different paths between the transmitter and receiver. Multiplexing is best suited to environments consisting of high multipath in which the various MIMO channels are uncorrelated.

The trade-off between diversity and multiplexing gains offered by MIMO systems is a well researched topic in literature. [75] demonstrated that both diversity and multiplexing gains could be simultaneously obtained, with a fundamental trade-off between the two. Since then, there has been a wealth of research into the diversity/multiplexing trade-off for MIMO systems [76]–[80]. For example, in [81], the authors suggest a framework for devising practical adaptive MIMO architectures, focusing on switching between three MIMO schemes: diversity, hybrid diversity/multiplexing, and multiplexing. In the context of adaptable 5G networks, it would be beneficial to let the network operator control the diversity/multiplexing gain through adaptive precoding.

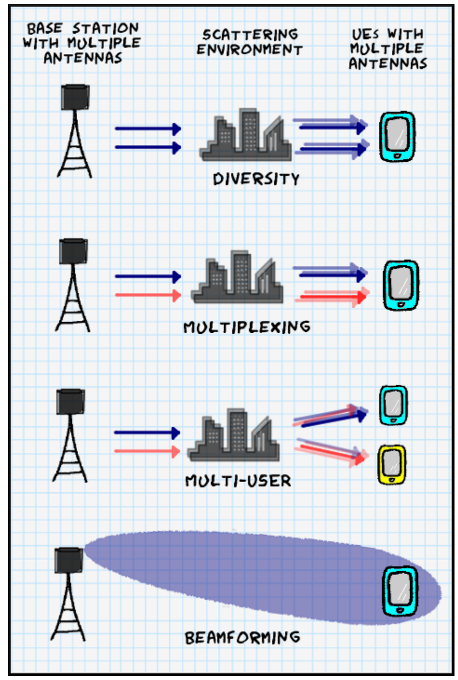

Fig. 4. MIMO can be utilised for many benefits including diversity, multiplexing, multiple access, and beamforming.

The diversity/multiplexing trade-off is already considered in LTE, which was designed to natively support the use of multiple antennas in both base stations and user devices, with both diversity and multiplexing configurations permitted. The receiver measures the channel elements and works out the rank indication, which indicates the number of symbols it can successfully receive. In open loop spatial multiplexing, the receiver then feeds back the rank indication to the transmitter. The rank indication depends on how well behaved the channel is. Spatial multiplexing works best in high-scattering environments when the channel elements are highly uncorrelated with each other, allowing the receiver to separate the received symbols from each other. When line-of-sight exists, the channel elements are generally highly correlated and diversity methods may be better suited.

For a more detailed overview of the use of multiple antennas in LTE, we refer the reader to [82], Chapter 5. While adaptively switching between diversity and multiplexing may be currently implemented in LTE, its usage is relatively basic. The advent of vastly greater number of antennas in 5G, both distributed and co-located, introduces many new challenges and considerations in this area, ensuring that adaptive switching between multiplexing and diversity will remain relevant in 5G research.

Adaptive Spatial Modulation (ASM) Spatial modulation (SM) is a MIMO technique which extends traditional digital modulation techniques such as quadrature amplitude modulation (QAM) into the spatial domain. In SM, only one transmit antenna is active at any time, with the index of the transmit antenna used to convey information. Blocks of bits are mapped to both a symbol from the constellation diagram, and a unique transmit antenna number chosen from the set of possible transmit antennas. Spectral efficiency is increased by the base-two logarithm of the number of transmit antennas.

SM takes advantage of the uniqueness and randomness properties of the wireless channel, since each antenna in the possible transmit antenna set will experience different channel conditions. The receiver can then determine the transmit antenna index, which is used in demodulation. Since only one transmit antenna is active at any one time, SM can be considered to be a type of single RF-chain MIMO. This results in a greatly reduced complexity compared to conventional MIMO, which requires an RF-chain per antenna. For more information on SM, we refer the reader to the following articles, [13], [14], [83], [84].

Spatial modulation offers yet another way of utilizing multiple antennas, representing a new type of modulation and bringing new challenges in this respect. Similar to the idea of adaptive modulation and coding, which adapts the coding rate and constellation size according to channel conditions, adaptive spatial modulation (ASM) [85], [86] aims to dynamically adapt the modulation order assigned to the transmit antennas according to the channel quality. As illustrated in [83], the fundamental trade-off in adaptive spatial modulation is between constellation size and the number of transmit antennas. In poor channel conditions, a small symbol constellation size is required as the distance between symbols is reduced. However, the poor channel may result in highly uncorrelated antennas, allowing the number of transmit antennas to be increased. Conversely, in good channel conditions, a larger symbol constellation and small number of transmit antennas may be preferable. Therefore, dynamic link adaptation has an important role to play in adaptive networks utilising SM.

Adaptive Precoding Precoding is a core concept in multiple-input multiple-output systems and refers to maximizing the signal at the receiver by applying appropriate weightings at each antenna to the multiple data streams being transmitted. Precoding essentially takes advantage of channel state information at the transmitter (CSIT) to perform processing on the signal before transmission. Techniques can be divided into linear and non-linear. Non-linear techniques such as Dirty Paper Coding (DPC) achieve the channel capacity at the cost of high complexity. Linear techniques, such as zero-forcing, block diagonalization, and maximum ratio transmission (MRT), are less performant but come with reduced signal processing complexity.

[87] demonstrates that in the case where the number of antennas is significantly greater than the number of users, as is the case in M-MIMO, simple linear precoders are close to optimal under favourable propagation conditions. [88], however, demonstrates that this does not hold true when realistic array deployment, taking the physical separation of antennas in account, is considered and that there in-fact remains a performance gap between linear and non-linear precoding for dense large scale arrays. This fundamental performance/complexity trade-off naturally leads to the concept of adaptive precoding. In this case, antennas become a fundamental building block for networks, with network operators possessing the power to decide how to use them and what precoding techniques to employ.

One currently existing example of adaptive precoding is the precoding matrix indicator (PMI) in LTE, which is passed from the receiver to the transmitter. The PMI controls the precoding step in the transmitter if diversity is selected, and prevents symbols from cancelling each other out at the receiver by controlling the phase shifts of the transmitted symbols. Adaptive precoding also enables the adaptive switching between diversity and multiplexing techniques. Typically, the UE selects the best precoder from a predefined precoder codebook that maximizes the transmission rate for a particular MIMO channel, and feeds this information back to the base station. The precoding choice may also depend on many factors including the number of users to be served, the number of antennas in the array, the signal processing complexity budget, and channel statistics. The concept of adaptive precoding is explored in [89]–[91].

Inter-Cell Interference Coordination (ICIC) In dense deployments of small cells, inter-cell interference becomes the limiting factor. ICIC techniques such as CoMP aim to convert this potential interference into useful signals. CoMP refers to a collection of techniques that involve coordination between multiple base stations/antennas during transmission and/or reception to improve the service provided to cell-edge users, and is still under development for LTE-Advanced. [92] discusses some of the deployment scenarios for CoMP in LTE-A and provides an overview of the main CoMP techniques. [93] provides a useful overview of CoMP techniques in both the uplink and downlink.

CoMP requires coordination between multiple base stations in order to mitigate inter-cell interference and potentially form useful signals. CoMP is generally categorized into two main groups (Fig. 5).

1) Joint transmission/reception (JT/JR): In the downlink, data is transmitted from each base station in the serving group simultaneously in order to boost the signal strength at the receiver. In the uplink, each base station in the serving group receives the signal from the UE. Signals from each base station are then combined and jointly processed. Data must be shared between each base station, placing increased load on the backhaul between cells.
2) Coordinated scheduling and beamforming: In the downlink, data is transmitted from only one base station in the serving group to the receiver at any time instant. In the uplink, cooperating cells schedule which base station will receive the data. Scheduling is coordinated among cells in the serving group to mitigate interference and select the base station that can offer the best service to the UE. This reduces the load placed on the backhaul between cells as data does not need to be available in each cell, only channel state information and scheduling decisions are shared among cells.

Even from such a brief overview of CoMP and without delving into finer details, it is apparent that multiple antenna use involving CoMP techniques affords choice to network operators, particularly in small cell architectures and DAS. It is the prerogative of the network operator to decide whether they

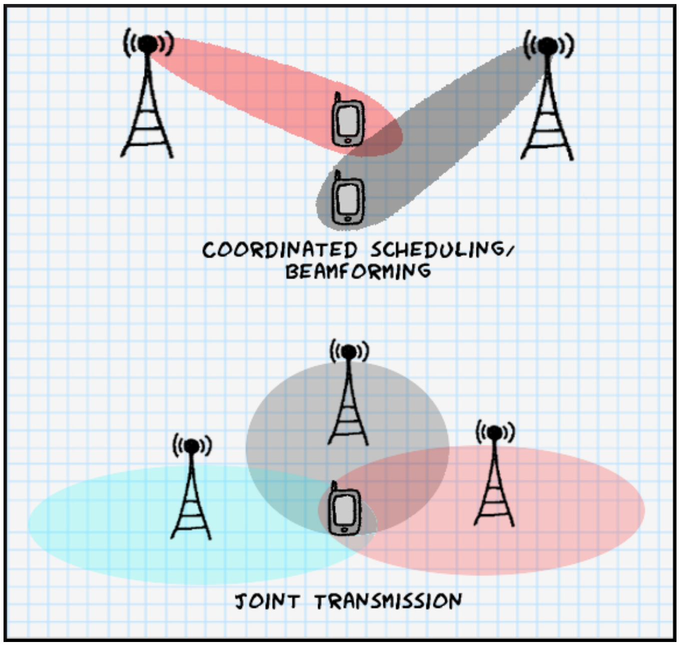

Fig. 5. Multiple antennas can be used to reap the benefits of CoMP, including coordinated scheduling/beamforming and joint transmission.

wish to employ CoMP techniques or not and if so, choose between JT/JR or coordinated scheduling/beamforming. Taking advantage of the benefits of CoMP involves choosing suitable clusters of cooperating base stations. These clusters may be assigned in a static or dynamic manner, possibly requiring the network operator to perform frequent re-selection.

In the case of JR and JT, the question of which entity performs processing is also relevant. Processing may be centralized, maximizing the load placed on the backhaul, or it may be distributed among base stations in the cooperating set. Cloud-RAN, which centralizes processing for multiple remote radio heads, represents a practical implementation of CoMP techniques (JR and JT). Cloud-RAN abstracts the processing power from the physical radio transmitters, allowing both baseband processing units (BBU) and remote radio heads (RRH) to be treated as resources in a flexible manner. Clusters of RRHs can be chosen according to user location patterns to form a cooperating set, connected to the same BBU.

In-band full duplex and multiple antennas In IBFD, multiple antennas can be used in a separated antenna configuration to improve SIC through passive methods that utilize the physical distance between transmit and receive antennas to attenuate SI, thereby allowing the network operator to avail of the benefits of IBFD such as potentially doubled capacity, reduced control plane latency, and faster collision detection. Alternatively, the network operator may decide to employ the antennas for MIMO in half duplex mode, to avail of multiplexing or diversity gains.

[94] discusses a scenario consisting of IBFD capable transmitters and HD capable devices in which uplink spectral efficiency is affected by self-interference at the BS. Antenna resources can be used to boost the receive diversity gain, or to improve self-interference cancellation. The authors demonstrate that there is a trade-off between the two options. [95] compares the performance gains achievable by either using antennas to enable IBFD communications, or increasing the capacity of an HD MIMO link. It is suggested that, under certain conditions, using antennas to enable IBFD communications can provide greater performance boosts, potentially motivating an adaptive scheme capable of switching between both options according to current conditions. [49] considers a device with two antennas, and compares the relative performance between using the antennas for IBFD transmission in D2D, or using both antennas in half duplex mode to communicate through the base station. Again, a hybrid scheme capable of switching between both options depending on the interference conditions may prove advantageous.

Distributed antennas The availability of large numbers of antennas in 5G presents network operators with many options. In dense deployments consisting of cheap low power nodes, the cost of acquiring additional antenna nodes may also be correspondingly cheap. Below, we examine three ways in which distributed antennas may be used:

- *Distributed Antenna System (DAS):* In a DAS, antenna elements are separated spatially and are connected to a common controller. The principal idea is to extend the coverage of a base station by distributing antennas throughout the environment, retaining the same power budget so that each antenna transmits with reduced power. DAS is popular in indoor environments, in which antennas distributed throughout a building connect to a macro base station (often located on the roof) and serve as repeaters to improve indoor coverage.
- *Distributed MIMO:* MIMO can consist of co-located[3] antennas as part of the same physical array, or distributed throughout the environment. [97] asserts that distributed MIMO systems can achieve higher diversity gain compared to co-located MIMO, as co-located antennas may experience a similar scattering environment. [98] discusses the use of MIMO in DAS, and the advantages it affords. Concepts such as adaptive precoding and the diversity/multiplexing trade-off for MIMO systems, which were discussed previously in the section, remain relevant here.
- *CoMP:* In interference limited environments, network operators may wish to avail of the benefits of ICIC techniques such as CoMP. Two main decisions present themselves here. The first is whether to employ JT and JR and incur the cost of higher load on the backhaul. The alternative is to use coordinated scheduling. The second decision relates to the selection of clusters of cooperating nodes.

C. New Waveforms

One of the defining characteristics of each generation change has been the question surrounding the choice of modulation

[3]The word 'co-located', as used in [96], represents antennas on the same array, as opposed to distributed throughout an environment.

format and MAC strategy. 5G is no different, and while multiple contenders are laying down challenges, there is no clear favourite in sight yet. Orthogonal frequency division multiplexing (OFDM) and orthogonal frequency-division multiple access (OFDMA) were chosen to be the modulation format and MAC strategy respectively for LTE due to the advantages they offered over the code division multiple access (CDMA) systems used in the preceding generation, including higher spectral efficiency and efficient realization using fast Fourier transform (FFT) and inverse FFT (IFFT) blocks.

Despite its advantages, OFDM's place in future 5G networks is challenged by new techniques [19] that aim to deal with some of its shortcomings such as:

1) Large out-of-band transmissions, resulting in interference issues. This also adversely affects the ability of carrier aggregation to exploit non-contiguous spectrum, a topic that is likely to play an important role in 5G.
2) High sensitivity to synchronization errors and Doppler shift. The European FP7 research project 5GNOW deems it essential to introduce waveforms that are less sensitive than OFDM to frequency misalignments [99]. In [100], the authors demonstrate that the high sensitivity of OFDM to frequency offsets in a multi-user scenario requires advanced interference cancellation techniques, in turn leading to complex yet low performance systems. Thus, one of OFDM's main advantages in the form of simplicity is lost.
3) Although we listed OFDM's spectral efficiency as an advantage, that was in comparison to previous generations, and there is potential for new techniques to further improve upon this. In particular, the need for a cyclic prefix in OFDM and the large side-lobes at spectrum edges reduce the spectral efficiency.
4) The strict synchronicity demands of OFDM introduces a substantial control overhead in the network. In particular, the emergence of machine type communication (MTC) as a major topic in 5G introduces new considerations in this area. With the introduction of massive numbers of devices to the network, coordinated access would generate huge signalling overhead, potentially flooding the radio access network. In this regard, a strong case is being made for techniques that facilitate uncoordinated access.

As a result, 5G sees a variety of candidate waveforms competing to satisfy the myriad of scenarios and requirements mentioned in Section I. Filter bank multicarrier (FBMC) schemes aim to achieve higher spectral efficiency than OFDM by suppressing large side-lobes through per-subcarrier filtering, and negating the need for a cyclic prefix by using narrow channels with flat gain. Universal filtered multicarrier (UFMC), also known as UF-OFDM, applies filtering to groups of adjacent subcarriers. This idea is based on the observation that asynchronicities tend to occur at block edges, while orthogonality can be maintained within the block itself. Due to the development of equalizers that approach OFDM in complexity, single carrier modulation (SCM) may be, as the authors of [101] suggest, a technique whose time has come again. The main potential for SCM in 5G would be in low latency applications, since delays related to the block processing of data can be avoided [19]. Generalized frequency division multiplexing (GFDM), first introduced in [102], is a multi-carrier modulation scheme with flexible pulse shaping that targets low out-of-band (OOB) emissions and frequency agility.

It is not within the scope of this survey to recommend any particular waveform. Instead, we recommend the following select few papers, [15]–[21] , which compare the relative strengths of some of the waveform contenders for 5G. The focus of the rest of this section is to examine how the new candidate waveforms for 5G can assist in enabling the creation of a versatile 5G network.

The diverse and demanding requirements for 5G necessitate flexible and adaptable solutions to be adopted across the entire network, including the air interface. Previously, in 2G, 3G, and 4G systems, the radio access network consisted of specifically designed hardware that was optimized to satisfy the key requirements for that generation. 5G requires a more adaptable approach, transitioning from the rigid, inflexible air interfaces of previous generations to a more versatile and reconfigurable solution.

This idea of a reconfigurable air interface is explored in [103]. The authors highlight the need for 5G to '*go soft*', with a reconfigurable RAN implemented in software. The software defined air interface (SDAI), enabled by software defined radio (SDR), consists of an intelligent controller and multiple configurable fundamental building blocks such as the frame structure, waveform, multiple access, modulation and coding, etc. Different services can be supported using different configurations of the fundamental building blocks, which are controlled through software. As an example of the concept, the authors provide a case study on the adaptation between OFDMA and sparse code multiple access (SCMA) to jointly improve both energy and spectral efficiency. The study reveals cross-over points between the two schemes with varying minimum average throughput threshold and cell radius.

In terms of designing an adaptable network, the SDAI concept offers numerous advantages. Through software defined radio, many aspects of the air interface become configurable, allowing the network to be tailored towards different services. In contrast to an air interface optimized for a singular application, we instead have a fluid and adjustable system. Achieving reconfigurability in every facet of the air interface presents several challenges. Current LTE networks already implement a form of adaptability through adaptive modulation and coding (AMC), in which the coding rate and modulation scheme are chosen according to the link quality. We have already discussed adaptive duplexing and multiple antenna use in the previous subsections. In this subsection, we focus our attention on the multiple access and waveform choice.

Although there are many waveforms being considered for 5G, each presents advantages and disadvantages depending on the scenario under consideration. For example, SCM techniques may lend themselves to low latency applications since they do not incur the delays associated with the block-processing of data. FBMC, on the other hand, may be preferable in an MTC scenario as it facilitates asynchronous access

[99]. Hence, an adaptable and flexible solution is required in relation to the choice of waveform and multiple access technique. Below, we explore some of the possible different strategies involving the selection of one or more waveforms for 5G that would lend themselves to the goals of flexibility and versatility:

*1) **Single Waveform - adjusting parameters of a configurable waveform**:* This option advocates the standardization of a single configurable waveform, which can be tweaked through tunable parameters. We can begin with a single malleable waveform and mould it according to our needs. This concept is best described as a software defined waveform (SDW), an idea that resonates with many of the current trends in 5G such as SDN and software defined radio (SDR). This option relies heavily on the softwarization of the RAN in order to be able to present configurable waveform parameters which can be adjusted according to the scenario to be supported. SDR is therefore an enabling technology, and the concept of a configurable waveform fits with the previously described concept of an SDAI. The configurable parameters form a numerology for the waveform, which define it for a particular use case. The content of this numerology, i.e. the parameters themselves, depend on the base waveform in use.

This idea of tweaking the parameters of a waveform according to the use-case is hinted at in [1], in which the authors envision a type of tunable OFDM. In this vision, OFDM would permit configuration through tunable parameters such as subcarrier spacing, cyclic prefix (CP) length, and FFT block size. For example, user specific subcarrier spacing and symbol period is considered in [104], which compares several variants of OFDM which employ either a cyclic prefix or zero postfix, and use either windowing or filtering.

Filtered-OFDM (f-OFDM) is presented as an enabler for a flexible waveform in 5G in [105]. In this vision, with f-OFDM, the assigned bandwidth is divided into several subbands. Each subband employs OFDM (or possibly other waveforms) with a numerology tailored to satisfy a particular service. The parameters of such a numerology may include subcarrier spacing, CP length, and transmission time interval (TTI). Asynchronous transmission across subbands is supported through subband-based filtering.

[106] identifies generalised frequency division multiplexing (GFDM) as a promising solution for 5G as a result of its inherent flexibility and highlights this point by demonstrating how different sets of GFDM parameters are conducive to particular scenarios. These parameters essentially form a set that characterize the waveform for a particular use case. In particular, [106] shows how GFDM can be tailored according to several broad 5G scenarios such as Bitpipe, MTC, and Tactile Internet. [107] highlights the need for a flexible PHY layer in 5G and a waveform with many degrees of freedom, and proposes a flexible FPGA implementation of GFDM that permits run-time reconfiguration. Multiple applications can be supported through configuration of several parameters such as filter coefficients, the number of subcarriers in a block, and the number of sub-symbols per subcarrier. GFDM's flexibility positions it well amongst the other 5G contenders. GFDM incorporates both CP-OFDM and SCM as special cases. In addition, [106] reports GFDM's suitability for MIMO systems. GFDM's advantages come at the cost of increased complexity; however, recent low complexity modem designs such as [108] aim to lower this cost.

The primary aim here is to use a configurable waveform to expose PHY flexibility to higher layers. The role that techniques at these higher layers perform, and the manner in which they interact with the PHY layer, is critical to the successful implementation and adoption of an SDW vision. Clearly the concept of SDW lends itself to a coupling with techniques such as SDR and SDN, such as the possibility of incorporating SDN and a centralized controller which defines the set of parameters for the waveform to be used for a particular scenario.

*2) **Multiple Waveforms - selecting from a pool of waveforms**:* 5G may be the first generation that permits the coexistence of multiple waveforms. Given a choice of waveforms, each suited to different use-cases, the waveform itself can be viewed as an addition to the resource pool. Different applications or services may benefit from the use of different waveforms, according to their specific requirements. For example, clustered device-to-device (D2D) pairs underlaying an OFDMA macro-cell may use a different waveform such as FBMC in order to reduce the leakage interference between devices. Mission critical applications such as vehicular traffic safety may require ultra low latency in order to prevent crashes between high speed vehicles, and hence may use a waveform or frame structure capable of supporting short TTIs. We are therefore motivated to investigate how multiple waveforms may impact upon one another and ultimately coexist.

Several works have begun investigations into the coexistence of various waveforms by characterizing the cross-waveform leakage interference. [109] considers a scenario consisting of asynchronous D2D communication overlaying an OFDMA macro-cell, and investigates the benefits of D2D pairs adopting new 5G waveforms. The authors generate interference tables characterizing the interference from several new waveforms onto an OFDM receiver. In [110], the authors investigate D2D communication in an OFDMA/SC-FDMA based cellular network, in which device-to-device pairs may use FBMC to reduce interference. [111] highlights the limitations of using a power spectral density (PSD) based model when evaluating the interference between OFDM/OQAM and CP-OFDM, and emphasizes the importance of considering demodulation effects at the receiver.

Cloud-RAN offers further possibilities for enabling multiple waveforms in 5G, as baseband processing units using different modulation schemes can be connected to remote radio heads. In essence, the network operator can choose which modulation scheme to use depending on the services being supported. The advent of softwarization permits this vision, negating the need to choose a single waveform for all of 5G, as modulation formats can be changed dynamically in software on both a device and a base station (or BBU). This permits network operators to use any modulation format they wish. There is a shift in emphasis involved in this vision from standardizing a particular waveform that all 5G networks must use, to standardizing a set of procedures and protocols that allow

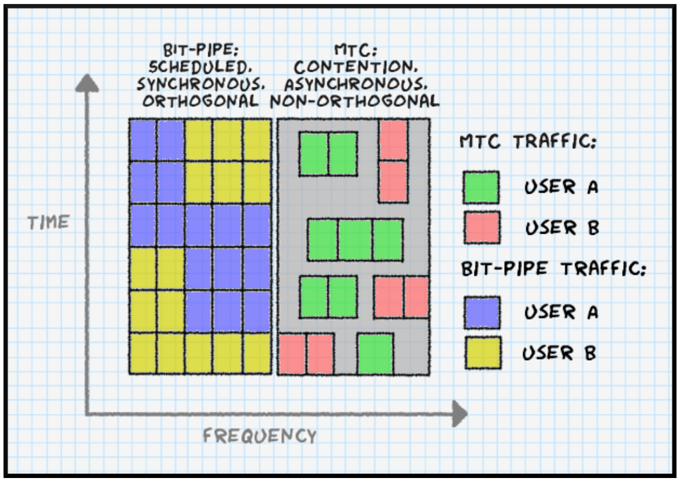

Fig. 6. Different services can be accommodated using a frame structure that can support different access procedures, and comprises both synchronous/asynchronous and orthogonal/non-orthogonal traffic types. See Fig. 2 in [99] for a broader visualization of the unified frame structure concept.

network operators to choose a modulation scheme from a set of possible candidates.

*3) **Adjusting the multiple access procedure and level of synchronicity**:* This option proposes choosing a single waveform that is suitable for many applications, and using it with different synchronization procedures and access methods.

At the beginning of this section, when discussing the motivation behind researching new waveforms for 5G, we discussed how the strict synchronicity demands of OFDM introduce a substantial control overhead in the network when the large number of MTC devices expected in 5G is considered. MTC is characterised by high-volume sporadic traffic consisting of short packet sizes, indicating that it may be best served using contention based access with relaxed synchronism. Hence, we first explore the possibility of using a frame structure that can support different access procedures, as well as different levels of synchronicity and orthogonality. Classical bit-pipe traffic can be serviced using scheduled access with strict orthogonality and synchronism. MTC traffic, on the other hand, may use contention based access and abandon synchronism in order to reduce the signalling overhead (Fig. 6).

We examine the findings of the 5GNOW project, which advocates the adoption of a unified frame structure to satisfy the various traffic types [99] to be supported in 5G. The concept of a unified frame structure is also described in [112], in which the authors advocate for the use of UFMC. The unified frame structure aims to be flexible and scalable, incorporating a mix of synchronous/asynchronous and orthogonal/non-orthogonal traffic types. In total, four traffic types are defined, with each targeting a different class of application or service. Each traffic type uses an access procedure, and level of orthogonality and synchronism, appropriate for the traffic that it accommodates.

Three of the traffic types abandon synchronism and hence do not incur the overhead and energy required by a closed-loop synchronization procedure. Instead, these traffic types could achieve coarse time-alignments by listening to the downlink, in an open-link synchronization procedure. [112] also suggests the use of autonomous timing advance (ATA) [113], whereby devices estimate their propagation delay in an open-loop procedure and adjust their transmission timing to compensate.

The allocation edges between synchronous and asynchronous traffic types are susceptible to both inter-carrier interference (ICI) and inter-symbol (ISI) interference. This fact motivates the authors of [112] to compare the relative suitability of both OFDM and UFMC to the unified frame structure, and recommend UFMC based on the results obtained. [114] also discusses the unified frame structure and compares the merits of three waveforms, OFDM, FBMC, and UFMC, in this context.

The concept of a unified frame structure demonstrates how various scenarios can be handled by a single waveform by altering the access procedure (scheduled/contention), and the level of synchronicity (closed-loop/open-loop with ATA). A flexible frame structure for 5G is also discussed in [115] and [116], which supports the dynamic adjustment of the TTI according to the service requirements of the link. Given the targeted 1ms latency support for mission critical applications in 5G, TTIs of no more than 0.2-0.25ms are required. Hence, latency critical links may benefit from a small TTI in the flexible frame structure, while high data rate users may prefer a longer TTI in order to reap the benefits of larger coding gains.

Another area in multiple access that has been gaining traction recently is non-orthogonal multiple access (NOMA). The conventional multiple access schemes used in previous generations, such as TDMA in 2G, CDMA in 3G and OFDMA in 4G, are all orthogonal multiple access schemes, allocating orthogonal resources in either the time, code, or frequency domains. In contrast, NOMA uses non-orthogonal resource allocation to accommodate larger numbers of users, which is particularly relevant for 5G. For more information, we refer the reader to [117], which provides an overview of NOMA and categorizes existing NOMA schemes into two groups: power-domain multiplexing and code-domain multiplexing. Interestingly, [117] also proposes the concept of software defined multiple access (SoDeMA), which can support diverse services and applications through adaptive configuration of available multiple access schemes. This resonates with the aforementioned idea of a software defined waveform (SDW), and highlights the ongoing trend towards softwarization of the network in response to the need for greater control and versatility.

III. System-Level Techniques for 5G

Having obtained a clearer idea in Section I of the scenarios and requirements to be satisfied in 5G, we now take a system-level view of the network. We chose to focus on SDN and cloud RAN, not only because they represent two of the largest topics in this area, but also because of the potential they possess in the context of enabling adaptable 5G networks. Both techniques aim to achieve a higher level of abstraction in the network, which brings an inherent increase in flexibility and the ability to dynamically control resources.

Software-defined networking abstracts network control into a logically centralized controller, decoupled from the data plane. Cloud-RAN abstracts processing power into a separate pool of resources that can be dynamically assigned as needed to remote radio heads. We also include a discussion on increasing network capacity through architectural changes and approaches to spectrum utilization, including small cells, device-to-device communication, cognitive radio, and millimetre wave communication.

A. *Software-Defined Networking (SDN)*

Traditionally the control plane of a network, which is responsible for managing the routing and flow of data, was implemented at a hardware level. As a result, altering the behaviour of a network required reconfiguration of a vast number of devices each containing vendor specific protocols – a costly process in terms of both time and money. SDN decouples the control plane from the data plane, allowing centralized control over the behaviour of the entire network. The rules for handling data can now be specified in software at the controller, which communicates with the data plane (i.e., switches, routers) through an open interface. As a result, it is possible to alter the entire behaviour of the network from a single logical point without needing to physically touch the hardware. This allows for greater efficiency in the utilisation of resources as the network can be reprogrammed to meet current demands. SDN is a key component of the 5G vision of flexible networks and will have profound implications on the manner in which resources are allocated and managed.

The essence of SDN is possibly best characterised by four of its core principles [118], [119]:

i) *Decoupling of control and data planes* This principle is the foundation of the SDN concept. It advocates the separation of the control plane into a logically centralized software controller which is capable of managing and altering the routing of data through the network. This separation has an implicit implication that the controller is in some way external to the physical equipment that it controls. Decoupled data and control planes co-located on the same device blurs the definition of SDN.

ii) *Logically centralized controller* The extracted control plane is logically centralized into a single controller with a network wide view. This logically centralized controller may in fact consist of multiple virtual or physical controllers operating in a distributed manner, depending on the scale of the network.

iii) *Open interfaces* One of the motivating factors behind SDN was to reduce the effort and cost associated with reconfiguring the vendor-specific devices in the network. An open, standardized interface between devices in the control and data planes, known as the southbound application program interface (API), is therefore a key principle of SDN. Fig. 7 illustrates the two primary interfaces in SDN: northbound and southbound.

iv) *Programmability by external applications* The controller in SDN allows for programmability by external applications through the so-called northbound API. This naturally lends itself to the concept of adaptability. It allows the network operator to view the myriads of physical hardware under its control as a single programmable entity which it can configure.

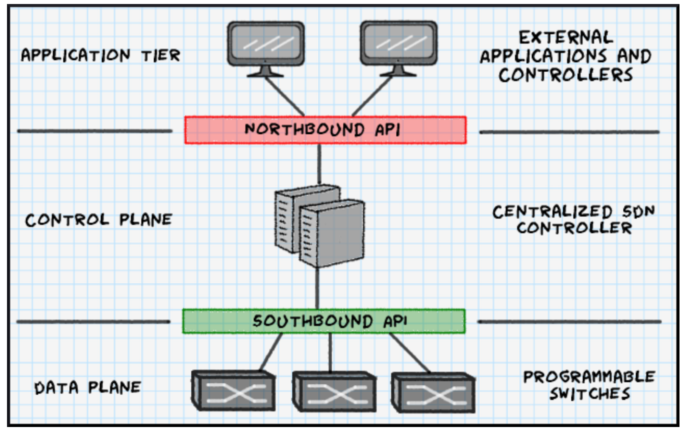

Fig. 7. Northbound and southbound APIs of SDN.

A more comprehensive overview of SDN and its implications in terms of programmable networks is provided in [26], in which the authors also provide a comparison between two of the most popular SDN architectures/standards; OpenFlow and ForCES. A survey of SDN and specifically OpenFlow is provided in [28]. Kreutz et al. provide an extremely comprehensive survey of SDN in [27].

In this section, we are primarily concerned about how SDN can be used to increase the versatility of 5G networks, and create and manage adaptable networks using radio access technologies as building blocks. SDN offers potential in this regard in the following ways:

- Wireless SDN: SDN itself is inherently adaptable, introducing greater abstractions into the network by decoupling the control and data planes. The flow of data through the network can be altered through programmable controllers. We first explore the flexibility that SDN introduces by examining its application in a wireless context, noting that SDN has thus far mainly been researched in the wired domain.
- Slicing: Slicing refers to partitioning resources and isolating the traffic between multiple coexisting virtual networks.[4]
- Gathering of statistics: SDN can be used to gather usage statistics and obtain a global view of the network. From a virtualization point of view, it allows the virtual network operator to make informed decisions about the management of virtual resources.
- Cloud-RAN and SDN: SDN offers a means to flexibly connect remote radio heads (RRH) to baseband processing units (BBU).

Wireless SDN So far, the SDN concept has mainly been

[4]As has become common parlance when discussing virtualization, we use the term slice to refer to a virtual network instance. A slice comprises the virtual resources that constitute that particular virtual network.

considered in the wired domain. In particular, SDN has found its application in data centres, with several works in the literature targeting this area [120]–[122]. SDN's development is continuously maturing as large corporations such as Google [123] adopt its use. Less work has been carried out applying the principles of SDN in the domain of wireless networks.

A few recent works have broached the topic of SDN in a wireless context. [124] explores the application of SDN to the wireless domain in mobile networks, and discusses some of its potential use cases and benefits including virtualization and quality of experience (QoE)-Aware Network Operation. The authors also describe a generic software-defined wireless network (SDWN) architecture using the 3GPP Evolved Packet System as a reference. In the proposed architecture, the southbound interface now connects to three types of entities: user plane entities in the core network, user plane entities in the RAN, and mobile nodes. [29] provides a useful survey into the primary trends and ideas involving SDN in the context of wireless networks, partitioning the literature into three main target areas: wireless local area networks (WLAN), cellular, and multi-hop wireless networks. Most research on wireless SDN has so far focused on WLANs, with virtualization and the ability to slice the network present as recurring themes. Research in the cellular area is divided into both the RAN and the core network. While we refer the interested reader to [29] for a more detailed discussion of wireless SDN, we provide a brief overview of current trends below:

- *Mobile*: Both [125] and [126] focus on the use of SDN in cellular core networks, highlighting that current core networks suffer from inflexible and expensive equipment. [125] makes first steps in exploring the application of SDN in cellular networks by proposing extensions to existing controller platforms and switches that enable high-level policies to be enforced based on subscriber attributes. [126] proposes a scalable architecture employing SDN concepts called SoftCell. SoftCell supports high-level service policies based on subscriber applications through fine-grained packet classification, which is performed at the access edge. In contrast, [127] focuses on the RAN and proposes SoftRAN, a software-defined centralized control plane for RANs. SoftRAN introduces the concept of a virtual big-base station which is an abstraction consisting of a central controller and all of the physical base stations in a given geographical area. This permits effective load-balancing and interference management within the encompassing area. [128] presents a promising architecture for mobile carrier core networks based on SDN principles, detailing its development and the use of a proof-of-concept prototype. Interestingly, the authors highlight the potential that a software-defined mobile network provides in terms of enabling innovation and permitting the creation of any network type on-demand, two focuses of this paper. [129] introduces an architecture incorporating the use of SDN techniques for wirelessly backhauled cells.
- *WLAN*: Prior to the advent of the concept of wireless SDN, the decoupling of control and data planes was present in the Control and Provisioning of Wireless Access Points (CAPWAP) [130] protocol specified by the Internet Engineering Task Force (IETF), which centralizes control in wireless networks. Although a technology-agnostic protocol, CAPWAP has only had bindings defined for 802.11. Odin [131], [132] is an SDN framework that introduces programmability in Enterprise WLANs, making it simpler to support and manage a wide range of services and functionalities such as authentication, authorization and accounting, policy, mobility, and load-balancing. Odin builds on a light virtual access point (LVAP) concept that greatly simplifies client management by abstracting association state and separating it from the physical access point (AP). Clients are logically isolated by providing every client with a unique basic service set identification (BSSID) to connect to, resulting in client-specific LVAPs. This mitigates the need for mobile clients to re-associate with access points, as its client-specific LVAP can be migrated between physical access points. OpenRoads [133], [134] can be thought of as a wireless extension to OpenFlow, allowing researchers to perform experiments in isolated slices of their production network. OpenRoads has been built and deployed at Stanford University, permitting multiple routing protocols, mobility managers and network access controllers to run simultaneously for experimental purposes. In OpenRoads, access points and base stations contain flow-tables which can be configured by a remote controller via the OpenFlow protocol. Multiple wireless technologies can be incorporated into OpenRoads, with WiFi and WiMAX nodes both used in the Stanford deployment. The authors envision OpenFlow as an enabling tool in their vision of a future mobile internet whereby users can move seamlessly between different radio technologies without being aware of or concerned about the manner in which connectivity is being provided. [135] presents a software-defined wireless network named AeroFlux that supports large enterprise WiFi deployments. Aeroflux achieves low-latency through a two-tier control plane. Near-sighted controllers, which are located close to access points, handle time-critical tasks. Global controllers handle events requiring a wider view of network state and which are not time-critical. Global controllers are also responsible for managing and instantiating near-sighted controllers. AeroFlux utilises the same LVAP concept as Odin, with each LVAP storing per-client OpenFlow and WiFi Datapath Transmission (WDTX) rules.
- *Infrastructure-less*: [136] explores how SDN can be beneficial in wireless infrastructure-less networking, focusing on wireless personal area networks (WPAN) based on IEEE 802.15. [137] proposes designs for SDN-based Mobile Cloud architectures in ad-hoc networks (Mobile Cloud proposes to wirelessly connect multiple mobile devices to provide cloud like services). In addition, [137] highlights two main challenges of extending the SDN concept to infrastructure-less networks; node mobility results in frequent topology changes and the controller-switch links are no longer wired. [138] demonstrates

the use of OpenFlow in Wireless Mesh Networks using a testbed named KAUMesh. SDN and OpenFlow have also been explored in the context of wireless sensor networks [139]. In a general sense, the extension of SDN to infrastructure-less networks is concerned with routing flows through a wireless backbone that is subject to frequent topology changes.

Slicing networks: In the context of this discussion, we consider OpenFlow due to its current dominance in the SDN landscape. In an OpenFlow architecture, data forwarding devices are considered to be switches and routers. OpenFlow-enabled switches consist of flow tables which are used to match particular data flows, garner statistics on each flow, and specify how they should be handled. The flow table entries are controlled by the SDN controller through a standardized southbound API. SDN, as implemented by OpenFlow, therefore consists of three main components:

1) Packet matching for flow-based routing.
2) Reporting of flow statistics for global network view.
3) Traffic isolation between different virtual networks.

Slicing refers to the task described in the third point above. In OpenFlow, this task is performed by a unit called FlowVisor [140]. FlowVisor sits logically between the SDN controller and the SDN-enabled device, and ensures that the controller can only alter flows belonging to its own virtual network. It therefore helps satisfy the core virtualization principle of isolation. In order to achieve this, FlowVisor partitions the flow-table, assigning a number of flow-entries to different virtual networks. It also partitions bandwidth resources by setting limits on the data rate of a set of flows for a particular slice. FlowVisor acts as a proxy between OpenFlow enabled hardware and multiple SDN controllers belonging to different virtual networks, using the OpenFlow protocol to communicate with both controllers and hardware. From the controllers' viewpoint, it appears as if they are communicating directly with the hardware (Fig. 8).

Gathering statistics: In addition to managing the forwarding plane, the OpenFlow protocol also permits per-flow counter statistics to be requested from OpenFlow enabled switches. Network monitoring can therefore be achieved through the addition of a monitoring module in the controller which gathers statistics. The retrieving of statistics from switches is generally implemented in a pull-based fashion in order to keep the complexity of switches at a minimum. Controllers must, therefore, periodically query switches for flow statistics, resulting in a trade-off between accuracy and network overhead. The ability to collect per-flow statistics in SDN has been the focus of several works in the literature [141]–[144]. For example, OpenNetMon [144] is an open-source software implementation that provides monitoring of per-flow metrics such as throughput, delay, and packet loss, and can be used to determine whether end-to-end quality of service (QoS) parameters are actually met. OpenNetMon was written as a module for the OpenFlow controller platform POX, a Python-implemented platform targeting research and education.

From a virtualization point of view, the availability of statistics allows the virtual network operator to identify un-

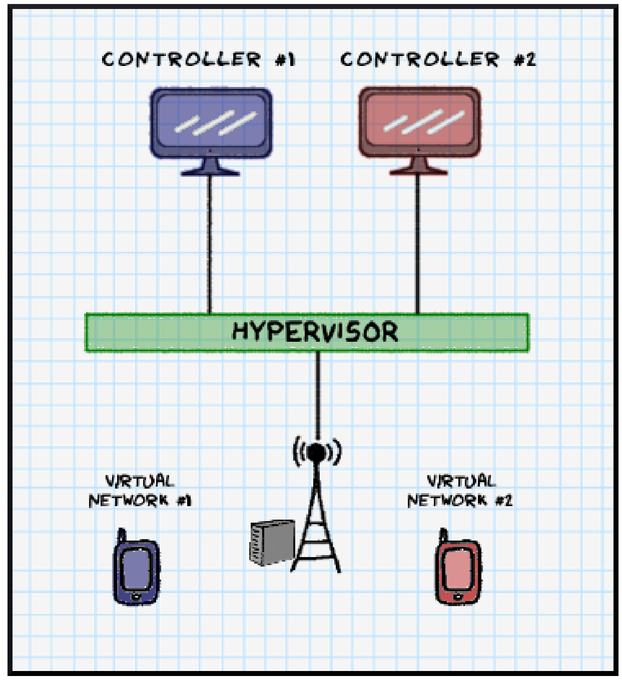

Fig. 8. A hypervisor-like element can be used to logically partition and isolate hardware, acting as a proxy between controllers and the hardware itself. A hypervisor is a piece of software that permits multiple virtual machines to coexist on a single hardware host.

derutilised virtual resources that can be released, and request additional virtual resources in places where the network is over-loaded. For example, in an area where multiple virtual base stations are reporting low usage, the virtual network operator may decide to release some of its virtual resources. Conversely, in an area where multiple virtual base stations are reporting high usage, the virtual network operator may decide to acquire more virtual resources in that area.

SDN and Cloud-RAN Cloud-RAN, discussed in the next section, consists of remote radio heads (RRH) and baseband processing units (BBU). The RRHs simply transmit and receive RF signals, and are connected to BBUs which perform the actual baseband and packet processing. The RRHs and BBUs are connected via the fronthaul link. SDN presents a flexible solution in the fronthaul link for connecting RRHs and BBUs. We discuss this idea in more detail in the next subsection when we outline the concept of reconfigurable fronthaul in cloud-RAN.

B. Cloud-RAN

The cloud-RAN paradigm proposes splitting the radio access network (RAN) into three components:

i) *Baseband unit (BBU) pool:* The BBU pool performs baseband and packet processing, separating and migrating this functionality from individual base station sites to a centralized location. One of the motivating factors for cloud-RAN is the so called tidal effect, in which the traffic experienced by a particular base station fluctuates both temporally and spatially as users travel to and from work each day. In cloud-RAN, BBUs can be dynamically assigned to overloaded areas as required, in accordance with the tidal effect.

ii) *Remote radio heads (RRH):* RRHs can be considered dumb compared to current base stations, as processing capabilities have been abstracted away. RRHs simply transmit and receive signals, perform analog-to-digital and digital-to-analog conversion, and send signals to/from the baseband unit (BBU) pool for processing.

iii) *Fronthaul link:* The fronthaul connects the RRHs and BBUs. Due to the large bandwidth requirements, optical fibre is generally used in the fronthaul. Signals are transmitted as either digitized radio signals over common public radio interface (CPRI), or analog signals using radio over fibre (RoF). Wavelength division multiplexing is used to separate signals. CPRI is more robust than RoF over long distances as it suffers less degradation; however, this advantage comes at the cost of increased bandwidth requirements.

One of the most apparent benefits of cloud-RAN is its adaptability to non-uniform traffic. In the traditional network architecture currently employed, base stations are designed to handle peak traffic loads, which can be several times higher than normal usage. Cloud-RAN benefits from statistical multiplexing gain by dimensioning the processing capacity of the BBU pool to be less than the sum of the capacities of individual base stations. This is motivated by the fact that base stations in different areas experience peak load at different hours of the day. Hence, cloud-RAN can adapt to traffic fluctuations throughput the day by permitting overloaded base stations to use more processing power.

Cloud-RAN provides numerous other advantages. By confining radio functions to RRHs and centralizing processing in BBUs, the cost of deploying additional radio heads to improve coverage is now reduced - an advantage which will be hugely beneficial in the ultra-dense networks envisioned for 5G. Better energy efficiency can be achieved as processing power can be dynamically allocated and BSs can be turned off when not needed. The cloud-RAN paradigm also facilitates the sharing of information between cooperating BSs, leading to improved spectrum utilization [145]. Finally, network upgrades and maintenance are much simpler.

The cloud-RAN concept alters the manner in which resource allocation is performed. Processing power is now a resource to be allocated as needed. In addition, cooperation between RRHs can be realised as the centralised BBUs have access to the channel state information and other information supplied by neighbouring RRHs. The ability to treat both RRHs and processing power as resources offers great potential in the pursuit of creating a flexible, adaptable 5G network. In this subsection, we explore how this potential may be realised. For a detailed survey of cloud-RAN, we refer the reader to [31].

RAN-as-a-service (RANaaS) One of the important questions in cloud-RAN surrounds the functional split of processing, i.e. which functions should be implemented locally at the radio head site, and which should be handled remotely in the processing pool. The various split options have differing requirements for the fronthaul in terms of both bandwidth and latency. [146] analyses several possible splits of the LTE baseband processing chain, taking into account bandwidth and latency requirements. [147], on the other hand, focuses on the opportunities provided by a flexible split, detailing the advantages and disadvantages of several options. In summary, the more lower-layer functions that are moved into the centralised processing pool, the higher the demands on fronthaul are in terms of latency and capacity.

This notion of a flexible split is the core concept at the heart of RAN-as-a-service (RANaaS), first introduced in [148]. RANaaS is motivated by the limiting requirement in cloud-RAN for high capacity, low latency fronthaul. Connecting RRHs and BBUs via fibre is expensive and difficult depending on the environment. Hence, RANaaS envisions different functional splits between decentralized entities (radio heads), and centralized processors (BBU pool) depending on the capabilities of the available fronthaul. Higher capacity fronthaul permits a higher degree of centralization, shifting lower-layer functionality into the processing pool. When high capacity fibre fronthaul is not available, lower-layer functions are implemented locally with a RANaaS platform offering centralised processing of higher layer functionality.

The RANaaS allows operators to use alternative cheaper fronthaul options, such as wireless or copper based solutions. Further work on achieving this flexible fronthaul split in cloud-RAN is detailed in [149]. The energy efficiency benefits of RANaaS are the focus of [150]. The benefits of the RANaaS concept are significant in the context of adaptable 5G networks, permitting the degree of centralization to be adapted to the capabilities of the available fronthaul. [151] examines cloud technologies for flexible 5G RANs and discusses the benefits of RANaaS. The centralization of processing and management can be adapted to service requirements, with different algorithms used according to traffic characteristics. This connects cloud-RAN with the radio access technologies in Section II, allowing them to be adapted according to the services to be supported.

Cloud-RAN and reconfigurable fronthaul Most works on cloud-RAN consider RRHs to be statically connected to a pool of BBUs, with the benefit arising from the statistical multiplexing gain. This statistical multiplexing gain can be maximised by permitting the dynamic reconfiguring of mappings between RRHs and BBUs according to traffic demands, which can significantly reduce the number of BBUs required [152]. [147] suggests that cloud-RAN introduces the possibility of using dedicated signal processing software for particular services. This also motivates the need for a dynamic, flexible fronthaul which is capable of associating RRHs with different BBUs running dedicated software depending on the service.

[153] argues that a one-to-one mapping of BBUs to RRHs is sub-optimal, and advocates for a flexible fronthaul architecture between BBUs and RRHs that permits configurable mapping. Two types of mapping between BBUs and RRHs are highlighted: one-to-one and one-to-many. One-to-one corresponds to a small cell scenario in which each RRH is connected to a single BBU. One-to-many relates to a cooperative scenario such as CoMP in which many RRHs are connected to the same

BBU. The mapping is achieved using a configurable switch consisting of optical splitters coupled with an optical switch (a lack of commercially available products forced the authors to use RoF and consequently optical switching). The notion of configurable fronthaul connecting BBUs and RRHs is further developed in [154], in which the authors again highlight the inefficiencies of one-to-one mappings and propose *FluidNet*, a framework employing a logically configurable fronthaul. BBU-RRH switching schemes are also discussed in [155], which proposes semi-static and adaptive schemes.

In the context of cloud-RAN, SDN is concerned with introducing flexibility into the fronthaul that connects RRHs and BBUs. As already noted, optical fibre is generally employed in the fronthaul due to the large bandwidth requirements. Signals can be transmitted either as digitized signals using CPRI, or analog using RoF. CPRI permits reconfigurable switching to be performed in the digital domain, while RoF requires switching to be performed in the optical domain, increasing the associated complexity.

Reconfigurable fronthaul, possibly utilising SDN principles, provides a means to flexibly connect the RRHs belonging to a virtual network to the corresponding BBUs for that network. In an alternative view, it allows two virtual networks to share a virtualized base station or antenna by routing the signals associated with each virtual network to the corresponding BBU for that network. This allows two virtual networks sharing the same hardware to use different modulation and duplexing schemes by forming connections to distinct and separate BBUs. It also facilitates cooperation among multiple virtual antennas by connecting each of the antennas in a cooperating cluster to a shared BBU.

Matching of signals is not required at the switch for the one-to-one and one-to-many scenarios, as the switch can be configured when a virtual network operator acquires an RRH and BBU. The entity controlling the physical substrate would be responsible for configuring the switch to map the RRHs belonging to a virtual network operator to the corresponding BBUs. The core principles of SDN, namely programmability and the decoupling of control and hardware, are applicable in this situation as they permit the mapping between BBUs and RRHs to be handled in software.

As well as the two types of mapping discussed above, we are also interested in many-to-one and many-to-many relationships between BBUs and RRHs. The possible relationships are illustrated in Fig. 9. In a many-to-one relationship, multiple BBUs are connected to a single RRH. The motivation behind this type of relationship would be to allow multiple virtual networks to share the same RRH, leading to the notion of a virtual antenna. In order to permit an RRH to be connected to two or more BBUs, the switch must be capable of identifying the signals belonging to the various virtual networks sharing the RRH and route them accordingly. In the OpenFLow realization of SDN, OpenFlow enabled devices are equipped with flow tables that contain the matching rules. OpenFlow operates at layer three, matching and routing packets. Matching is generally performed using layer three and layer two packet headers. Since cloud-RAN performs a split in the stack with layer one RF processing performed at the RRH and layer one baseband processing performed at the BBU, matching is therefore problematic as layer two and three headers are not available. Instead, novel techniques need to be developed in order to make this a reality.

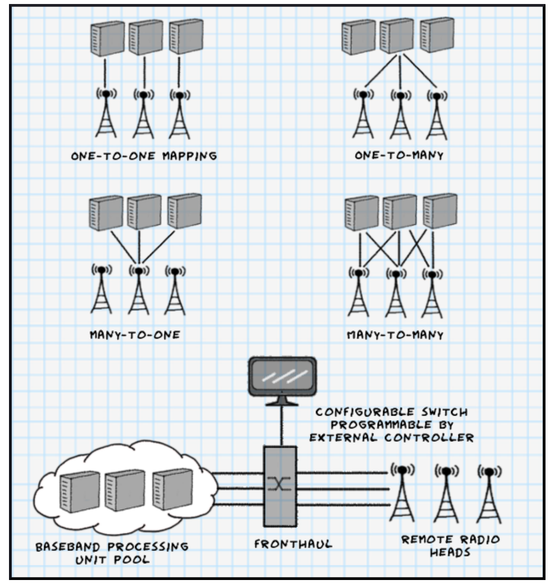

Fig. 9. SDN principles applied to the fronthaul in cloud-RAN would permit the dynamic reconfiguration of the various possible relationships between radio heads and processing units.

C. Increasing Capacity: Architectural Changes and Spectrum Utilisation

The requirements for 5G place huge demands on the network, such as the ability to handle a 1000x increase in current traffic volumes and provide a 100x increase in the edge data rate. Increasing the amount of available spectrum and using existing spectrum more efficiently represent two of the most effective approaches for increasing capacity. Approaches of the former category involve migrating towards higher frequency bands in search of unused spectral real-estate, such as the recent interest in millimetre-wave bands. Approaches of the latter category involve increasing the reuse factor of spectrum through network densification, enabling direct communication between devices, exploiting underutilised spectrum using cognitive radio, reusing the same spectrum for uplink and downlink using IBFD, and allowing full reuse of spectral resources through space division multiple access using MIMO techniques.

Of the techniques listed in the previous paragraph, two have been discussed already (IBFD and MIMO). In this section, we focus on methods to increase the available bandwidth (millimetre wave and cognitive radio), and on the architectural changes that may arise out of the need to utilise spectrum more effectively (small cells, direct communication between devices, and device-centric architectures).

1) Small Cells and Device-Centric Architectures: Network densification is one of the primary solutions to meet the capacity requirements of 5G [35]. Network densification involves the addition of vast numbers of small cells to the network. This effectively brings the network closer to the user and allows each small cell to service fewer users. The capacity gains arise from the aggressive frequency reuse permitted by a small cell architecture; however, the increased interference resulting from this represents the biggest obstacle to overcome. The term small cell is used to describe any low-power node that operates over a short range to complement the encompassing macrocell. A survey of dense small cell architectures is provided in [156].

Cells have always been the fundamental building block in mobile networks, with the classic hexagonal cellular model for base stations instantly recognisable even outside of the field. In this cell-centric architecture, the base station is the core element. Based on received signal strength, mobile terminals choose a single base station to associate with from a possible set. Cell-edge users generally experience reduced performance as a result of interference and reduced signal power. [6] envisions that this may be the focus of a disruptive change in 5G and envisions a device-centric architecture in which the focus is shifted from the base station to the user device. In this vision, devices connect to multiple base stations simultaneously for greater performance. The authors cite network densification, cloud-RAN, and cooperative communication techniques as some of the contributing factors to this vision. We already highlighted the theme of network densification, which in effect aims to increase frequency reuse at the expense of increased interference. Device-centric architectures aim to improve the performance of devices experiencing high interference by allowing the mobile terminal to connect to multiple access points simultaneously.

[157] advocates for a paradigm shift in 5G network design, guided by a principle of no more cells, from a cell-based coverage model to a user-centric approach facilitated by the use of cloud-RAN. In this user-centric approach, high-power macro-cells handle control signalling while data is transmitted using low-power small cells. This idea of a control-plane/data-plane split between macrocells and small cells is also developed in [158], which introduces the concept of a Phantom Cell. A Phantom Cell is a macro-assisted small cell in which the control plane is provided by an encompassing macrocell in a lower frequency band, while the user data-plane is provided by the small cell at higher frequencies. A survey of existing literature on the control-/data-plane separation for cellular radio access networks is provided in [159]. [160] discusses to what degree various control-/data-plane separation proposals address the main challenges in network densification, and suggest that the separation of control- and data-planes may be an enabler for D2D and CoMP for 5G.

The decoupling of control- and data-planes is not the only separation of transmission streams being proposed for 5G small cell networks; the decoupling of uplink and downlink in cellular networks has also been proposed and discussed in several works [161]–[163]. Traditionally, cell association has been performed on the basis of received signal strength at the user equipment, implicitly favouring the downlink. [161] argues that while this sufficed for traditional networks in which the transmit powers of macrocells were quite similar, the heterogeneity of future networks calls for a revision of cell association. In particular, downlink and uplink can have sufficiently different SINRs in a network consisting of nodes of varying transmission powers, resulting in the downlink and uplink of a single UE using different base stations. The performance of a decoupled association approach is examined in [164], which shows that using different association strategies for uplink and downlink results in an improvement in the joint uplink-downlink rate coverage in heterogeneous networks when compared to the traditional coupled association.

The decoupling of the data and control planes offers great flexibility to the network operator, enabling a user to be connected to multiple nodes simultaneously while remaining under a single locus of control. The ability to connect to multiple cells is greatly facilitated by a user-centric design, and offers a way to help mitigate the inter-cell interference associated with network densification. There is a strong link here with the multiple antenna approaches described in Section II-B, particularly ICIC techniques such as CoMP. The decoupling of uplink and downlink also increases the versatility of the network, permitting operators to use different cell association techniques for both uplink and downlink. The idea of a software defined duplexer described in Section II-A offers potential in this area, making it possible to isolate and pair any bands for uplink and downlink.

The decoupling of the control and data planes, as well as uplink and downlink, provides an operator with the ability to create multiple information flows through a set of nodes. Depending on the application being serviced, the operator may use this ability in order to meet the specific demands of a particular user.

2) Device-to-device Communication: Conventionally, devices are not allowed to form direct links with each other using licensed spectrum. The need for greater capacity, and hence greater spectrum utilization, however, has led to the advent of direct communication between neighbouring devices using the encompassing cell's spectral resources. By allowing nearby devices to establish direct links, D2D [36] negates the need to make a round trip via the base station and offers the potential to improve overall system throughput, spectrum efficiency, and energy consumption.

Spectrum sharing in D2D can broadly occur in two formats: overlay and underlay. In overlay, D2D capable devices communicate in parts of the spectrum left free by the cellular users (CU), while in underlay, the D2D devices fully reuse the bands occupied by the CUs. Underlay permits greater spectrum utilization compared to overlay at the cost of increased interference introduced to the CUs. For maximum performance, D2D should utilise both underlay and overlay simultaneously, both reusing the resources occupied by the cellular users and operating in free slots.

D2D communication can also utilise either the uplink or downlink resources of the incumbent users; however, the majority of the literature considers uplink resource sharing for three reasons. Firstly, some of the pilot information broadcast in the downlink is crucial and should not be interfered with. Secondly, in the uplink, all of the interference introduced by the D2D users onto the cellular users is experienced at the base station, making it easier to manage through resource allocation. Finally, in the case of FDD, uplink bands are often underutilised due to asymmetric traffic loads.

Device-to-device communication offers a further choice to network operators with regards to how they use their licensed spectrum. Permitting direct communication between devices within a cell allows the offloading of intra-cell traffic, and also opens up a wide range of possibilities for proximity services based on discovery of nearby devices. The challenge in using D2D lies in protecting the incumbent CUs from the interference introduced by D2D pairs. A vast number of works in the literature have proposed resource allocation and power-loading procedures for D2D communications to deal with this issue. We also note the potential for cognitive radio techniques in this area, with the D2D pairs treated as secondary users and the CUs forming the set of primary users.

3) Millimetre Wave (mmWave): Unlike the previous research areas that we discussed, mmWave does not constitute a specific technology, and is not easy categorized as either a RAT or a system-level technique. MmWave is concerned with taking advantage of the vast amount of spectrum available in the range of 30 to 300 GHz. Bands at these frequencies have not previously been considered for cellular access, due to rain attenuation, atmospheric absorption, and huge propagation losses compared to lower carrier frequencies. Despite this, mmWave is seen as a promising technology with applications in indoor environments and back-hauling of small cells. Due to the poor propagation characteristics, beam-forming is generally employed to achieve high antenna gain, essentially making mmWave communications directional and placing great emphasis on the importance of a line-of-sight (LOS) link. While mmWave itself may not refer to a specific technology, it is the above implications of using it that have disruptive ramifications for the PHY layer.

MmWave offers huge potential in achieving the 100x data rate increase, particularly for scenarios requiring huge data rates such as virtual reality applications. However, due to its reliance on a LOS link and its susceptibility to blockages, mmWave may not be suited to environments in which the user is mobile or whereby frequent environmental changes result in intermittent blockages. As an example, mmWave may provide excellent service to customers streaming video in a coffee shop. However, if the coffee shop becomes busy at lunch then the constant movement through the environment may result in an intermittent link, forcing the service provider to use alternative methods to maintain the required level of service.

The susceptibility of mmWave communication to blockages and its poor propagation characteristics can also be used to its advantage. In a small cell scenario, the propagation losses of mmWave communication act as a natural way of mitigating inter-cell interference and isolating cells. This natural isolation effect is further intensified in indoor environments. MmWave access points can be deployed in rooms with full frequency reuse, as the walls between rooms act as an isolating buffer between cells.

For more information regarding mmWave communication, we refer the reader to [32], [33]. Millimetre wave, like many of the technologies discussed in this paper, offers the potential to meet the service requirements being suggested for 5G. However, it also brings challenges such as range issues, sensitivity to blockages, and processing power consumption. An extensive overview of the challenges associated with mmWave can be found in [34]. Research into mmWave is still at an early stage, and it is unclear what role it will have in 5G networks, particularly in the context of adaptable networks. It is clear that mmWave is suited to high data rate applications, but it may not offer high reliability due to propagation characteristics. Hence, mmWave may constitute another addition to a network operator's arsenal, its use dependant on the service being supported.

4) Spectrum Sharing and Cognitive Radio: Spectrum sharing offers great potential in the pursuit of greater capacity by allowing underutilised frequency bands to be shared by multiple entities. This breaks from the traditional model of exclusive-access licensing, in which a single entity is granted sole use of a specified band. While critical to the evolution of wireless networks, the concept of spectrum sharing presents both technical and regulatory challenges regarding the coexistence among systems.

[165] views cognitive radio as an enabler of many different forms of spectrum sharing, and discusses the consequences of various spectrum sharing regulations in the context of cognitive radio. The term cognitive radio was first coined by Mitola in his seminal paper [166], which outlined an extension of software defined radio with model-based reasoning about the rules and policies governing spectrum access. We consider a broad definition of cognitive radio as an advanced form of radio, the core concept of which generalizes the idea of multiple access [22] through the ability to make intelligent decisions regarding the use of a shared channel, informed by policy description and information obtained by observing the radio environment.

Spectrum sharing can be categorized into horizontal sharing, in which all entities have equal priority, and vertical sharing, in which lower priority secondary users use the licensed band of a primary user. Cognition, i.e. the ability to sense the radio environment and accordingly make decisions regarding transmission, can be beneficial in both types of sharing. In horizontal sharing, cognitive radio techniques can be employed to ensure the friendly coexistence of both systems. In a vertical sharing system, cognitive radio can assist in enabling secondary license holders to utilise shared spectrum in a manner that is not harmful to the quality of service of incumbent users.

Cognitive radio has been one of the most popular topics in wireless communications research over the last decade, with numerous surveys dedicated to detailing developments in the area. For a recent, comprehensive survey on the evolution of cognitive radio research, we refer the reader to [22]. In the rest of this subsection, we focus on spectrum sharing opportunities for 5G, where cognitive radio will have a key role to play.

- **Sharing in Licensed Bands** Spectrum sharing in licensed bands is a way of increasing the bandwidth available to operators. Traditionally, entities have been awarded licensed bands with exclusive usage rights. New spectrum sharing concepts are challenging this idea, permitting the sharing of underutilised licensed bands between entities according to stipulated agreements. The entity that possesses the primary license for a spectrum band may not necessarily be a mobile network operator, with sharing in TV and radar bands also widely considered and investigated [24]. For a recent comprehensive survey on spectrum sharing schemes for licensed spectrum, we refer the reader to [23].

Two broad models are currently being advanced for vertical sharing:

1) Licensed Shared Access (LSA): LSA is a two tier model for spectrum sharing in licensed bands. The top tier in LSA consists of incumbent users, who have guaranteed protection and are capable of monetizing any underutilised spectrum that they may own. The second tier consists of secondary LSA licensees, who can get short term access rights with a guaranteed quality of service to the underutilised spectrum licensed by incumbents. LSA is initially targeting the secondary use of two International Mobile Telecommunication (IMT) bands for mobile services: 2.3GHz in Europe, and 3.5GHz in the US. In Europe, the 2.3GHz band is utilised by military and aeronautical radar, emergency services, and wireless cameras. In the US, the 3.5GHz band is used for maritime radar. Protection of the incumbents by sharing in a non-interfering manner is of critical importance. Fortunately, incumbent activity in these bands is often localized in time and/or space, making it possible for potential secondary use inside specified areas, or at specific times.
2) Spectrum Access System (SAS): SAS differs from LSA in the number of tiers defined [167], consisting of three tiers in comparison to just two in LSA. The top two tiers in both systems are similar, with incumbent users occupying the top tier and secondary license holders (known as primary access licensees in SAS) comprising the second tier. The additional third tier in SAS has the lowest priority and is known as general authorized access (GAA). GAA users are entitled to use spectrum on an opportunistic basis with no interference protection guarantees, and require active management to ensure that they do not interfere with either tier one or two users. SAS is currently defined for usage in the US market in the 3.55GHz-3.7GHz range.

The two models have in common a high degree of control of the spectrum by the incumbent, who decides when and where to license it for secondary use, and predicable availability of spectrum, from the secondary user's point of view.

- **Sharing in Millimetre Wave Bands** Although research into mmWave communication is still at an early stage, the feasibility of spectrum sharing in mmWave frequency bands is already being investigated [168]. Due to the use of narrow directional beams, and depending on the transmitter density, mmWave communication systems can be considered noise-limited rather than interference-limited [169]. This makes spectrum sharing a promising technique for mmWave bands, since multi-user interference is naturally avoided, even when users transmit using the same spectral resources in an uncoordinated fashion.

  The sharing of spectrum licenses in mmWave bands without any coordination is an interesting prospect for a network in which all users have equal priority spectrum access rights, and is made possible by the propagation characteristics of mmWave frequencies. Uncoordinated sharing is investigated in [170], with results showing that license sharing among operators increases the per-user rate in comparison with an exclusive license system. This work is extended in [171] which demonstrates the importance of narrow beams on the feasibility of spectrum sharing, with low densities of users also favourable. A multi-operator system in which networks share both base stations and spectrum is also investigated.

  Secondary licensing, whereby a network with an exclusive-use license can sell a secondary license to another operator with stipulated interference restrictions, represents another option for spectrum sharing in mmWave bands. Secondary licensing may be preferable over uncoordinated sharing for networks in which one entity requires a guaranteed quality of service. Restricted secondary licensing is investigated in [172], with results showing that coordinated sharing can permit a secondary system to achieve good rate coverage while guaranteeing the performance of the primary system. Secondary network performance is shown to improve with the use of narrow beams and when the network densifies.
- **Sharing in Unlicensed Bands** The search for additional spectrum to boost the capacity of cellular networks has led to interest in utilizing unlicensed bands to supplement the licensed spectrum owned by operators [173]. Unlicensed bands, such as the 2.4GHz Industrial, Scientific and Medical (ISM) and the 5GHz Unlicensed National Information Infrastructure (U-NII) bands, are typically used by low-power, short-range access technologies such as WiFi (802.11) or Bluetooth (802.15.1). Permitting cellular systems to operate in these bands requires considerations about how to achieve fair and friendly coexistence in order to ensure that cellular technologies do not swamp these bands.

  Currently, there are three primary types of unlicensed access proposed for LTE: LTE-Unlicensed (LTE-U), Licensed Assisted Access-LTE (LAA-LTE), and MulteFire. Although they are being proposed for LTE, the three schemes warrant inclusion in this paper as it is possible that the underlying spectrum access concepts will have a role to play in 5G, and that these schemes will be a precursor to those employed in 5G.

  1) LTE-U [174]: LTE-U, first introduced by Qualcomm [175], enables operators to increase capacity by using unlicensed spectrum in the 5GHz U-NII band for short range communications. LTE-U has two specified operational modes: supplemental downlink (SDL) and TDD mode. In SDL, unlicensed spectrum is used solely for the downlink, whereas TDD mode permits unlicensed spectrum to be used in both uplink and downlink.

LTE-U aggregates unlicensed spectrum with a licensed 'anchor' band, which provides control signalling and, if operating in SDL mode, the uplink also. If a cell is under-loaded, the network operator uses its own licensed spectrum exclusively, and does not avail of any available unlicensed bands.

2) LAA-LTE: LAA-LTE supports listen-before-talk (LBT), differentiating it from the LTE-U concept which is similar in almost every other aspect. With LBT, the shared medium is scanned for activity before every transmission. LAA is part of the 3GPP standardization activities and is suitable for adoption in regions which have regulatory requirements requiring the use of LBT at a millisecond scale [176], such as Europe and Japan. LTE-U, on the other hand, was designed outside the open standards bodies and can only be deployed in regions without regulatory stipulations regarding the use of LBT, such as US and China. LAA is specified for downlink operation in LTE Release 13, with the 3GPP currently working on specifying LAA for uplink operation in LTE Release 14.
3) MulteFire [177]: Unlike LTE-U and LAA-LTE, which aggregate unlicensed spectrum with an anchor in licensed spectrum, MulteFire targets the operation of LTE solely in unlicensed spectrum such as the global 5 GHz unlicensed band. MulteFire is based on LAA-LTE, using elements such as listen-before-talk (LBT) in order to coexist effectively with other access technologies that may also be using the same band. MulteFire enables organizations that do not possess licensed spectrum, such as businesses, to install and manage their own local LTE network, analogous to the deployment model for WiFi. This can be used to augment commercial cellular networks, or operated privately instead.

The demand for more spectrum appears to be making spectrum sharing a necessity. In response, regulatory efforts to define spectrum sharing systems, discussed above, are currently in various stages of development. It is possible that the majority of new licenses issued under 6GHz will be shared licenses, with the practice of issuing exclusive-access licenses gradually retired. Even in bands above 6GHz, early indications suggest that spectrum sharing will also have a role to play, with both uncoordinated and secondary sharing being actively researched for mmWave communications.

IV. Relationship between RAT and System-Techniques

In Section I, we highlighted that the requirements for 5G are extremely diverse, requiring a versatile network capable of adapting to the service demands placed on it. There are a multitude of technologies being considered for 5G in order to meet these demands, each varied in its advantages and disadvantages. In Section II, we surveyed some of the new radio access technologies being considered for 5G in the context of the choices and flexibility they afford. In effect, given the wide range of service requirements, new techniques may only offer advantages in certain scenarios. The role that new system-level techniques have to play in both directly introducing greater flexibility, and managing adaptable networks is very important. In this paper, the relationship between the new radio access technologies and the emerging system-level techniques for 5G is a key focus. Specifically, we are interested in examining how they may complement and assist each other in the pursuit of creating a versatile, adaptable network. In the first part of this section, we explore some options that can be used to enable this relationship and bridge the gap between radio access technologies and emerging system-level techniques in a manner that facilitates the realization of a versatile 5G network. We then summarize the future research directions for some of the key technologies covered in this survey, focusing on the challenges involved in enabling complementary relationships between them using the options explored in the first part of the section.

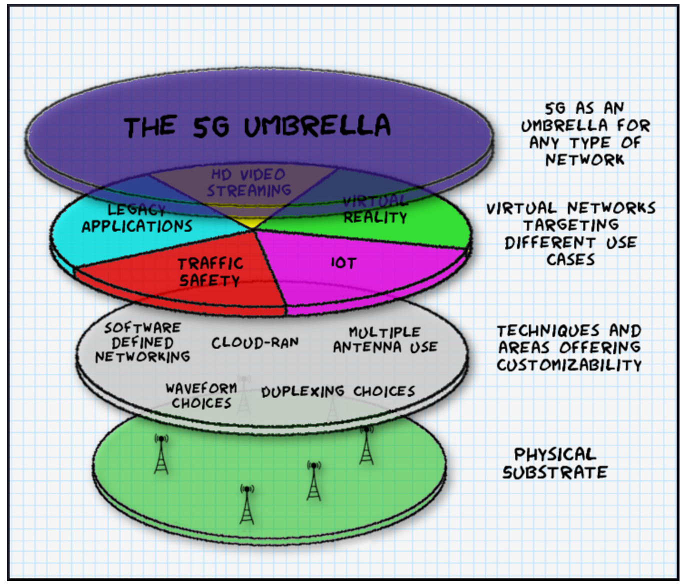

Fig. 10. 5G represents a unifying banner which encompasses all types of networks, allowing customized virtual networks which target specific services and use-cases to be instantiated.

Part A: Options for enabling the RAT - Network relationship

1. Virtualization*:* Virtualization abstracts the services provided by a network from the underlying physical resources that enable them. In effect, infrastructure becomes a pool of resources from which virtual networks can be instantiated. In the literature, a lot of emphasis has been placed on the sharing benefits associated with virtualization, and this is arguably the main motivating factor for the growth of research focusing on virtualization in 5G networks. The sharing of resources reduces operational expenditure (OPEX) and capital expenditure (CAPEX) for Mobile Network Operators (MNO), removing the barrier of high initial investment in infrastructure associated with upgrading the network. While the importance of this cannot be understated, it is not the main concern in this paper. Instead we focus on another benefit of virtualization that we expect will grow increasingly important over the next few years, namely the ability to create a virtual network that is customized for a particular service [178].

The requirements for 5G can almost be considered contradictory in many ways. It is difficult to imagine a network that is optimized to provide data rates of 1 Gbps to a virtual reality application, while also being optimised to provide connectivity to thousands of low data rate sensors. In order to reconcile this apparent contradiction, it is important to note that not every scenario requires each of the above requirements. Mission critical applications may demand low latency, as well as high data rates, but may only consist of a few devices connected to the network. MTC is likely to consist of massive numbers of devices with low power consumption requirements, but may not require high data rates.

Each scenario can be mapped to a specific type of network which has been optimised to satisfy the corresponding requirements of the scenario. Virtualization offers a platform to achieve this, allowing each scenario to be mapped to a virtual network which has been instantiated according to the requirements of that particular scenario. 5G, therefore, might not be considered one single type of network but rather an umbrella for a host of customized virtual networks (Fig. 10). Nothing exemplifies this vision better than the co-existence of traditional user data and machine type communication (MTC) in 5G. Sensor networks were considered to be a different type of network to cellular networks in previous generations given their hugely different requirements. 5G may aim to unify all types of network under the one banner, enabled by virtualization.

Virtualization provides the practical means to realise the flexibility required in 5G networks by allowing customized virtual networks to be created according to the requirements of different scenarios and use-cases. Virtualization can be used to present a well-defined interface to the emerging flexible radio access technologies so that these customized virtual networks can be truly tailored according to the targeted use-cases. It can also make use of system-level techniques that provide us with the flexibility to construct customized services and virtual networks, and dynamically manage them. While the radio access technologies constitute the building blocks, system-level techniques allow us to build something useful out of them, with virtualization forming the link between the two.

Virtualization is not a new concept in information and communications technology (ICT) and is widely used in wired networks. The advent of virtualization in wireless networks requires the introduction of new business models. [25] provides a comprehensive survey of wireless virtualization and neatly generalizes the roles that may exist in the new business models. In effect, infrastructure is owned by infrastructure providers (InP) and utilised by service providers (SP) who lease virtualized resources. Further granularity can be introduced into models through the creation of specialised roles such as the mobile virtual network provider (MVNP) which leases resources from an InP and virtualizes them, or a mobile virtual network operator (MVNO) which manages the virtual resources and assigns them to SPs. The abstraction

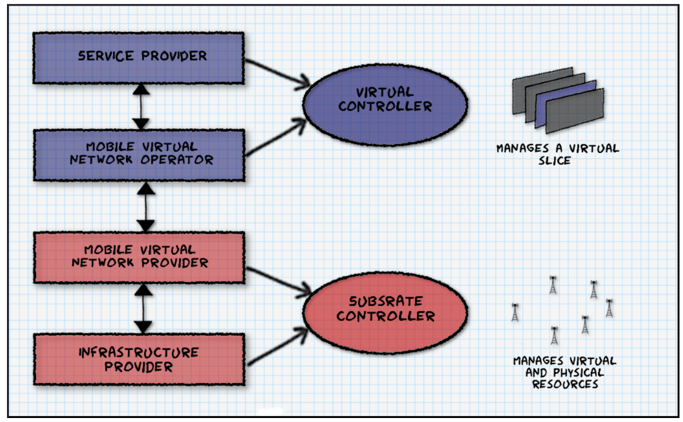

Fig. 11. Virtualization will introduce new roles into the telecommunications space. 5G should strive to take advantage of new value-chains by transferring increased power and control to the various emerging entities, providing them with the ability to tailor their own networks and innovate.

that virtualization provides between services and the physical resources on which they run exemplifies the type of progressive change that 5G must achieve. 5G must take advantage of these new business models and present service providers with the power to innovate and directly steer the development of networks in the future.

The flexibility that virtualization affords must be enabled at two levels; the substrate controller and the virtual controller [25]. The substrate controller is used by InPs/MVNPs to virtualize and manage the substrate physical network and is responsible for instantiating virtual networks according to the SP's/MVNO's needs. The virtual controller is used by the MVNO/SP to manage their own virtual slice and can be used to further tailor the virtual network to their needs using the resources that have been provided to them. Fig. 11 illustrates the different emerging business roles, and the entities under their control. It is also possible that the infrastructure owner and service provider are the same entity, i.e. that a network operator may choose to virtualize its physical resources in order to better utilize them. The network operator could then provide virtual network slices as a service, where each virtual slice is tailored to meet the demands of a particular service [179].

2. Cognitive Networks: We focus on the concept of a cognitive network as first defined in [180]: *A cognitive network is a network with a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals.*

We explicitly distinguish the cognitive network concept from that of a cognitive radio. A cognitive network possesses end-to-end goals, giving it a network-wide scope. In contrast, a cognitive radio possesses user-centric goals giving it local scope. The two concepts share common traits, however. Both concepts share similar models of cognition, learning from past experiences which influence decisions made in the future. Cognitive radio implements actions based on its observations through tunable parameters supplied by software defined radio. Cognitive networks on the other hand, dealing on a network-wide scope, require tunable parameters in the form of a software adjustable network (SAN) [180], [181].

The cognitive network definition has similarities to an earlier concept called the Knowledge Plane, described in [182]. The Knowledge Plane construct is described as '*a distributed cognitive system that permeates the network*', with the stated objective of creating a new kind of network that is capable of assembling itself based on a high-level description, detecting faults, and repairing itself. While much of the Internet's remarkable success has resulted from its core design principle of transporting data through the core without concern for what purpose the data serves, this has also resulted in severe limitations in terms of management, configuration, and fault diagnosis, each of which requires manual attention. The Knowledge Plane concept aims to construct a network based on cognitive systems that is able to make low-level decisions on its own, based on current network conditions and high-level descriptions of its design goals.

The concept of a cognitive network is elaborated upon in [181], which emphasises the importance of end-to-end goals. In effect, all elements in the network involved in data flow are part of the cognitive process, capable of providing information about the network and offering adaptability. The network should not be reactive, but should instead be able to make decisions based on predictive models constructed using past observations. In summary, the cognitive network inputs observations of network performance, uses these observations in a decision making process, and implements actions based on these decisions through adjustable network elements.

In order to be effective, the cognitive network requires extensive knowledge of network state for the decision-making process. Focusing on obtaining network state information, the cognitive process must have access to state across the entire network. Knowing the state of the entire network is somewhat unrealistic and, as a result, the cognitive process should be able to deal with incomplete information. Often the process will only require a subset of state information, obtaining the relevant pieces through filtering. The layered nature of networks provides a blockage in terms of the flow of state information in the network. Often a layer may be able to provide information that could potentially influence an adaptation at a different layer. Hence, cognitive networks must operate cross-layer.

[183] provides a survey of trends in the development of communication networks. While the survey, and much of the cognitive network literature, pre-dates the emergence of 5G as a primary research goal, the content is still relevant. In a similar theme to the discussion in the previous paragraph, the survey focuses particularly on cross-layer design and the representation of knowledge, with the cognitive loop of particular importance. Artificial intelligence techniques that are potentially applicable in cognitive networks are also presented.

Wireless cognitive networks are also the focus of [184], which emphasises the business and management aspects. Interestingly, the authors identify that a complementary idea to the cognitive networking idea is to simply have cooperating networks with different RATs, from which a network operator can choose the one that best suits their needs. This is similar to the idea of customized virtual network slices presented in the previous subsection. In effect, a virtual slice gives an operator a customized network which has been tailored to their needs, whereas cognitive networking gives an operator a network that is able to adapt itself according to the demands placed on it.

A cognitive network requires adjustable network elements that allow it to implement a set of actions based on the decisions it makes. In this regard, a cognitive network is limited by the flexibility of the network itself. If the cognitive process is unable to adjust the network based on the decisions it makes and in accordance with its end-to-end goals, then the application of the cognitive network is fruitless. Instead, a SAN is needed which presents tunable or modifiable components, allowing the cognitive process to adjust one or more layers in the network stack belonging to various network elements.

Cognitive networks offer great and obvious potential in the context of adjustable 5G networks. The cognitive network removes the need for an operator to tune the network, and is instead capable of autonomously adapting itself to the various service requirements as required. In addition, the radio access technologies presented in Section II offer the adaptability required by a cognitive network to be effective. Each radio access technology, such as duplexing or multiple antenna use, offers choices and modifiable elements that the cognitive process can utilize to adapt the network accordingly. Emerging system-level techniques such as cloud-RAN and Software Defined Networking, described in the previous section, also offer adaptability that can be used to alter the operation of the network. State information obtained at the radio access level may influence adaptations at the system-level, and vice versa. In this regard, the cognitive network concept unifies the radio access technologies and emerging system-level techniques. In essence, the diverse service requirements and flexible technologies make 5G a potentially excellent fit for integration with the cognitive network concept.

The concept of a cognitive network is a broad topic with many different techniques fitting the description, yet the realisation of a truly cognitive network remains unseen. In [182], published in 2003, the need for an adaptable network designed using artificial intelligence and cognitive techniques was identified. Thirteen years later, our networks are arguably more adaptive, but this adaptivity is confined to certain parts of the network and arises from the use of algorithmic techniques applied in these areas, rather than an inherent intelligence permeating the entire network. The lack of a true SAN has restricted the development of the cognitive network concept; however, it may be on the cusp of experiencing its coming of age moment. Similar to the way in which advances in SDR preceded and enabled a plethora of research in the area of cognitive radio, the current movement towards a software defined RAN, coupled with software defined networking techniques, may herald a renewed interest into extending the cognitive radio concept to the entire network.

Part B: Future directions and challenges

With the commercial roll-out of 4G LTE systems well under way, 5G is now firmly the focus of the wireless community. However, research on 5G is still relatively young and, while we may have an idea of the scenarios to be supported and the technologies that may potentially be beneficial, the final constitution of 5G is still unknown. What is clear, however, is that 5G will need to be much more adaptable than previous generations. The technologies and techniques discussed in this paper are likely to play a role in 5G in some shape or form. Based on the current literature, we have extrapolated research trends in order to present a survey of the possible ways that the chosen technologies can facilitate an adaptable, versatile 5G network. However, much work is still needed to make this goal a reality. In this subsection, we focus on the relationship between RAT and system-level techniques. We first highlight the potential for the system-level techniques listed in Section III to be used in conjunction with the techniques described in Part A of this section: virtualization and cognitive networks. We then provide an overview of how each of the RATs described in Section II fits into this vision.

Software Defined Networking*:* Software defined networking resonates with the trend towards increased softwarization, and offers the ability to dynamically alter the flow of traffic through a network. As stated in Section III, SDN has, thus far, mainly been considered in the wired domain. One of the greatest challenges for SDN in the context of adaptable networks is its application in the wireless domain. The advent of wireless SDN would result in the decoupling of control and data planes in the radio access network, with the control plane programmable through centralized controllers. This could facilitate more intelligent load-balancing and interference management between cells, particularly in a small cell environment.

As described in Section III, SDN could also be a supporting technology for virtual networks, facilitating the separation of traffic through the slicing of networks. In order to enable a vision of customizable virtual networks, there is a need to extend the concept of slicing to base stations and antenna arrays. SDN offers promise in this regard, capable of managing the traffic flows through a base station and partitioning the backhaul resources of a base station - whether it is wired or wireless. We envision base stations and antenna arrays equipped with the capability to match packets and dynamically manage flows. The SDN controller would be incorporated into the substrate controller, responsible for the allocation, set-up, and management of virtual resources. A hypervisor-like entity would act as a proxy between the hardware and the virtual controllers for different virtual networks, permitting each virtual network to coexist on the same hardware and manage their own virtual resources. [30] provides a survey of virtualization hypervisors for SDN networks.

The concept of virtual access points and virtual base stations is already present in the literature. We have already encountered the concept of a light virtual access point (LVAP) in both the Odin [131], [132] and AeroFlux [135] architectures. In both architectures, each client was provided with a specific LVAP which could be migrated between physical access points, mitigating the need for clients to re-associate. Per-client OpenFlow and WiFi datapath transmission (WDTX) rules are stored by LVAPs. CloudMAC [185] is an architecture for performing 802.11 MAC layer processing in the cloud which utilises SDN paradigms. Physical access points (AP) are considered dumb and simply forward MAC frames to virtual access points (VAP) which could be potentially located deep in the network. The VAPs handle the processing and generation of MAC frames, with OpenFlow used to manage the binding between physical APs and VAPs. CloudMAC is not targeted at achieving performance gains (testbed evaluation shows CloudMAC achieves similar performance to normal WLANs, with small additional latencies due to the tunnelling overhead), but instead targets greater flexibility.

Each of the above SDN-based frameworks targets access point virtualization in WLANs. Although we are primarily concerned with cellular networks in this paper, we provide the above examples to demonstrate the potential of SDN to assist in the slicing of base stations and access points. Given the proliferation of interest and research into virtualization, virtualizing base station resources has become an important topic. WiMAX base stations are the focus of [186] and [187], while several patents also exist for virtualizing base stations in cellular networks [188], [189]. It is not within our scope here to provide an extensive overview of techniques for virtualizing base stations and access points; instead, we simply wish to demonstrate the potential of SDN in this pursuit. Note that not all techniques for base station virtualization are required to employ SDN techniques. We refer the interested reader in this area to [190], which provides an overview of radio access network virtualization, including the feasibility of virtualizing base stations.

In Part A, we introduced the concept of a software adaptable network (SAN) in the context of a cognitive network. Essentially, the application of a cognitive network is limited by how adaptable the hardware is [181]. In order for the cognitive process to be effective, it must be able to implement actions based on its decisions by adjusting and configuring the network. A software adjustable network presents modifiable elements at one or more layers that can be adjusted by the cognitive process. From the names alone, it is clear that SDN could be a valuable addition to a SAN. SDN transforms switches and routers in the network into modifiable elements that can be configured by the cognitive process.

In the OpenFlow architecture, flow-entries in the flow table generally consist of three components [26]:

- Matching rules to associate incoming packets with flows. Matches are generally made against information in packet headers.
- Instructions to specify how to handle particular flows by dictating a set of actions to be applied.
- Counters to collect statistics for particular flows.

By modifying the instructions on how to handle particular flows, the cognitive network is able to implement actions based on its decisions through flow-based routing.

One particularly relevant attribute of SDN to cognitive networks is its programmability by external applications. This programmability makes it easy to separate the cognitive, decision-making *brain* of the network from the hardware itself, and fits the vision for a software adjustable network.

In addition, SDN facilitates the gathering of network-wide statistics. This can be beneficial to adaptive schemes which may adjust a particular network element in order to suit a particular service. While OpenFlow provides per-flow counter statistics, further research is needed to determine fully how SDN can assist an adaptive 5G network by providing it with information. In particular, the coupling of SDN and cognitive networks needs to be further investigated in this regard, with SDN capable of providing input to the cognitive process. In the context of virtual networks, the substrate controller can also benefit from usage statistics when allocating virtual resources, ensuring that sufficient resources are reserved according to the needs of its client virtual networks.

Cloud-RAN*:* Cloud-RAN abstracts the radio head in a base station from the processing power, centralizing the latter. This leads to statistical multiplexing gains, hence reducing the OPEX costs for network operators. In the context of adaptable networks, processing power can now be considered a resource and assigned to radio heads. Similar to SDN, cloud-RAN's strength lies in the abstraction it achieves and the resulting flexibility it affords. Cloud-RAN decouples the processing power and the physical radio heads, providing the flexibility to treat either RRHs or BBUs as a resource depending on your viewpoint. In effect, cloud-RAN implements a type of virtualization of the radio access network. Antennas and processing power form an underlying pool of resources which can be assigned to different virtual networks as required.

The flexibility of the BBUs, enabled by SDR, allow the virtual network operator to customize the low-level details of their network according to their needs. This could allow the virtual network operator to control the choice of duplexing method or waveform through the software in the BBU. In essence, cloud-RAN isolates the radio head as a fundamental building block, and offers the means to customize everything else through the flexibility of BBUs. The idea of virtual network slices is still very much in the concept stage. However, if it is to become feasible, cloud-RAN appears to be a very attractive enabling technology and may be an important line of research in the future.

Another major issue in cloud-RAN in the context of adaptable networks is the flexibility of the fronthaul. Current solutions are very rigid in their implementation, connecting RRHs to a fixed pool of BBUs. The benefits provided by more complex mappings between BBUs and RRHs motivate the need for a reconfigurable fronthaul in cloud-RAN (Fig. 9). While solutions such as *FluidNet* [154] target reconfigurable fronthauls, focused research is still needed in this area. In particular, the application of SDN in a reconfigurable fronthaul may prove to be beneficial.

In a similar manner to SDN, cloud-RAN also facilitates the cognitive network concept by enabling the idea of a software adjustable network. The software adjustable network consists of modifiable elements which allow the cognitive process to implement actions based on its decisions. Cloud-RAN offers several sources of modification. Firstly, processing power can be dynamically assigned to RRHs in accordance with traffic demands. Secondly, with reconfigurable fronthaul, cloud-RAN could allow services to be handled using dedicated BBUs that are running signal processing software optimized for that particular purpose. Finally, the RANaaS concept permits the adaptable splitting of signal processing functions according to the available fronthaul and the service to be supported.

Cognitive Radio and Small Cells*:* Cognitive radio can be considered to be a subset of the cognitive network concept, applicable only at the radio head. Hence, while cognitive networks possess end-to-end goals, the policies dictating the decisions in cognitive radio are more user-centric. Although cognitive networking has been restricted by the lack of a software adjustable network that permeates all aspects of the network, research into cognitive radio has proliferated in the past decade on the solid foundation of software defined radio (SDR).

From the above description of cognitive radio, the similarities with cognitive networking are evident. In a cognitive radio, the idea of a software adjustable network is reduced to software defined radio. Cognition in cognitive radio is also generally narrower in scope, being primarily concerned with the coexistence of systems in common frequency bands.

The advantages that cognitive approaches can offer in 5G have already been highlighted, and remain relevant in the discussion of cognitive radio. Primarily in this paper, we have examined how emerging techniques can be used to create an adaptable network. In effect, the focus of this paper has been on the reconfigurable requirement of a cognitive system, rather than the cognitive capabilities themselves. In cognitive radio, the reconfigurability aspect is often satisfied by software defined radio. We believe that the new techniques showcased in Sections II and III, and especially their potential for enabling adaptability, will result in an extension of the principles of cognitive radio to the entire network. Hence, we do not see cognitive radio as a building block of the network, but rather as a tool to be employed in certain cases.

From the brief overview of spectrum sharing activities in Section III-C-4, cognitive radio techniques appear to have a key role to play in 5G by enabling the coexistence among systems in common frequency bands. However, the use of cognitive radio may not be limited to managing the coexistence of different systems in spectrum sharing schemes; cognitive radio can also be used to manage the spectrum access of a single system with heterogeneous user types. An example of this would be D2D, in which direct communication using the encompassing cell's spectral resources is only possible if the incumbent cellular users are not affected.

Another example in which cognitive radio can assist in managing the spectrum access of users belonging to the same network involves the use of femtocells. Femtocells are small, short range cells deployed in areas of poor macrocell coverage, such as rural or indoor areas. They are designed to coexist with macrocells; however, in-band interference from the femtocell may affect the macrocell. Cognitive radio offers the potential to mitigate this interference. In effect, the femtocell is the secondary user of the operator's licensed spectrum, while the macrocell is the primary user. A survey of interference mitigations techniques using cognitive radio in femtocell networks is provided in [191].

The idea of using cognitive techniques in femtocells can be generalised to any type of small cell. Network densification increases capacity through greater frequency reuse at the cost of increased interference. The large scale random deployment of small cells with a lack of coordination makes the coexistence of small cells very challenging. Cognitive techniques offer the potential to deal with this interference in an intelligent manner, permitting the coexistence of heterogeneous small cells without requiring carefully planned cellular deployment. [192] investigates a self-organizing optimization for small cells using cognitive techniques which provide the ability to sense the radio environment, make intelligent decisions, and adjust their operational parameters accordingly. [193] also examines the potential for cognitive small cells to coexist in a multi-tier cellular wireless network, using stochastic geometry to obtain design guidelines. Finally, the application of cognitive radio in emerging areas, including small cells, is the focus of [194].

***New Waveforms**:* The choice of waveform has generally been the defining characteristic of generations in the past. Currently, it is not clear what the 5G air interface will look like. Multiple waveform candidates are being considered, and 5G may see the evolution of OFDM through the adoption of one of its variants, or a shift to a filter-bank based scheme. Regardless of the waveform chosen, the 5G air interface will need to move away from the rigid solutions of the past, and present a more configurable interface. This idea is captured by the concept of a SDAI, described in Section II-C. The SDAI consists of a radio access network implemented in software. The RAN comprises of configurable fundamental blocks such as duplexing, multiple access, modulation and coding, and waveform. While the authors in [103] provide a case study for the multiple access block, switching between OFDMA and SCMA, much work is needed to make the idea of a software-defined RAN a reality.

With regards to choosing a waveform for 5G, we outlined several options that would permit the required level of adaptability to be achieved. These options included choosing a configurable waveform, allowing the coexistence of multiple waveforms, and choosing a single waveform but varying the access procedure. While each option was founded on current trends in the literature, research in each of these three areas is not mature and extensive work is still required to make these feasible. For example, it is not clear what waveform would serve as the base for the configurable waveform, or how the relevant controller would interface with the waveform in order to tailor it towards different services. For coexistence of multiple waveforms, the leakage interference between different waveforms is very important. Recent works have begun to characterise this; however, there is a need for much more investigative research in this area.

There is an ongoing trend towards softwarization of the RAN. The concepts mentioned in Section II-C, such as software defined radio (SDR), software defined air interface (SDAI) [103], software defined waveforms (SDW), and software defined multiple access (SoDeMA) [117], each aim to increase the versatility of the air interface. Key parts of the access network become adjustable and programmable through software, permitting adjustment in response to specific needs. This propensity for an increasingly software defined RAN may result in a software adjustable network (SAN), exhibiting a strong resonance with the concept of a cognitive network. Hence, instead of a rigid one-size-fits-all approach to designing the air interface, as was the case in previous generations, future RANs may be much more fluid and intelligent by design, capable of adjusting themselves according to current traffic and usage demands.

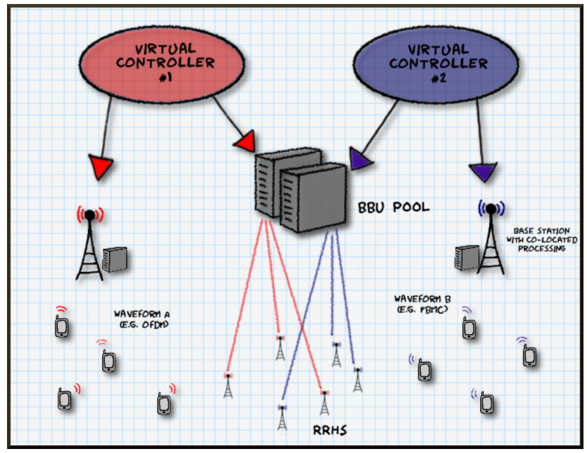

Fig. 12. Cloud-RAN allows different virtual networks to use the waveform best suited to the service requirements that they wish to satisfy.

We have suggested that 5G may be different, defined instead by its malleability rather than its air interface alone. In Section II-C, we highlighted the possibility that 5G may permit the coexistence of multiple waveforms. This would allow a choice of waveform during the instantiation of virtual networks. This involves a change in thinking, from standardizing a single waveform that all 5G virtual networks must use, to standardizing an interface that allows virtual networks to choose any modulation scheme at the time of instantiation. Cloud-RAN makes this possible, as BBUs can be configured to use any modulation scheme through the advent of softwarization. We are particularly interested in allowing multiple virtual networks to coexist on the same hardware, yet use different waveforms. Cloud-RAN enables this, allowing the RRHs belonging to separate virtual networks to be connected to different BBUs, each using different modulation formats (Fig. 12).

***Duplexing**:* In-band full duplex offers many advantages such as potentially doubled spectral efficiency, faster collision detection, and reduced control plane latency. However, it also introduces new types of intra-cell and inter-cell interference into the network, as well as residual self-interference. As a result, the performance of in-band full duplex systems is dependant on the interference profile of the cell and, in many cases, IBFD may not outperform traditional half duplex techniques. This represents a major challenge for the integration of IBFD in 5G, and motivates the concept of hybrid duplexing (as discussed in Section II-A). Hybrid duplexing is seen as a necessary measure if IBFD is to be adopted as a viable technology, and constitutes an important line of research in IBFD. While the concept of hybrid duplexing is starting to be explored in the context of cellular access, much more work is needed to investigate its usage in other areas, such as IBFD D2D communications, IBFD relaying, and dynamic spectrum access.

We propose to allow the virtual network operator to fully control the choice of duplexing scheme. Cloud-RAN again permits this vision, with the duplexing scheme customizable through the BBU in use for a virtual network. When a virtual network operator acquires a BBU and connects it to a radio head, the virtual controller can dictate the duplexing scheme in use through software. The virtual operator may be presented with many choices including which duplexing scheme to use, and choosing which bands to pair for uplink and downlink. If the radio head has SIC capabilities, the virtual controller must also decide how to utilise them; increased spectral efficiency or reduced control plane latency are both possible, as outlined in Section II-A.

[195] outlines the advantages of a cloud-RAN architecture coupled with IBFD communications, particularly in mitigating the BS-to-BS/downlink-to-uplink interference introduced by IBFD. The centralization of processing allows the BBU to perform cancellation of the BS-to-BS/downlink-to-uplink interference since the downlink signal of neighbouring RRHs is known by the BBU.

Again, the increased number of choices that IBFD introduces into the network, coupled with the adaptability that cloud-RAN permits through BBUs, offers potential in the context of cognitive networking. More choices and increased levels of adaptability lead towards a software adjustable network, a keystone of the cognitive networking concept. When simultaneous transmission and reception is selected, IBFD also offers the ability to present a continuous input stream of information into the cognitive process to aid the decision making process, even during transmission.

In the context of small cells, SIC capabilities can facilitate the decoupling of uplink and downlink [163], described in detail in Section III-C-1. A software controlled duplexer allows any combination of bands to be paired for uplink and downlink. This enables a device to associate to different small cells, which may operate in different bands, for uplink and downlink.

Finally, the advent of IBFD has implications for the allocation of spectrum. Spectrum is often designated as either TDD or FDD prior to allocation, with uplink and downlink bands also marked in the case of FDD. However, IBFD removes the concept of uplink and downlink. Matters are further complicated in the case of hybrid duplexing, in which the concept of uplink and downlink sometimes exists depending on the duplexing mode in use. The introduction of IBFD and hybrid duplexing would require fundamental changes to the way spectrum is designated and auctioned.

Multiple Antenna Use: 5G is likely to see an explosion in the numbers of antennas distributed throughout the environment. The theme of densification in 5G will see a proliferation of small cells underlaying macro-cells, which may be equipped with large antenna arrays. It is this availability of antennas in the environment that enables a higher level of flexibility, allowing operators to utilize multiple antennas in whatever way they wish. In effect, antennas become a fundamental building block of the network.

The addition of large numbers of antennas to the environment offers many potential advantages, but also introduces many challenges. Network operators are faced with many choices about how they may wish to use the distributed antennas at their disposal, as outlined in Section II-B. ICIC schemes based on the use of multiple cooperating antennas offer the ability to mitigate interference between small cells. Distributed MIMO presents an alternative option, offering either multiplexing or diversity gains depending on the channel. The diversity/multiplexing trade-off, therefore, remains relevant. Spatial modulation is another area offering many benefits. Deciding which techniques to use, and when, represents a research objective moving forward.

Of the system-level techniques considered in this paper, multiple antenna use offers the most apparent links with cloud-RAN. Cloud-RAN can enable the flexibility that multiple antenna use affords. Cloud-RAN abstracts the actual antenna from the associated processing, allowing both processing power and radio heads to be viewed as resources. RRHs form the basic building blocks for the virtual network, while the decoupled BBUs allow the VNO to utilise the RRHs whatever way they wish. In effect, it becomes easy to allocate extra antennas to a virtual network and connect to a BBU, allowing co-existing virtual networks to utilise antennas according to their needs.

Given a large array of virtualized antenna elements, a virtual network may only wish to acquire a small number of them and benefit from the use of regular MIMO. Alternatively, they may wish to acquire a large number of antennas and avail of the advantages that M-MIMO has to offer. The question of how many antennas are sufficient depends on the number of users to be accommodated, which can be expected to fluctuate. As a result, the allocation of antennas to particular virtual networks can be a fluid process, with antennas acquired and released by virtual networks as needed. In addition, antenna selection for the different virtual networks must be performed by the substrate controller, allowing for the possibility that the optimal choice of antennas for different virtual networks may overlap.

In the case of distributed RRHs throughout an environment, the virtual network operator may wish to acquire antennas for either distributed MIMO or CoMP. In the case of distributed MIMO, multiplexing gains depend on the richness of the scattering environment, which in turn depends on the antenna selection. The centralized aspect of cloud-RAN also permits coordination between selected RRHs, particularly for the JT and JR option in CoMP. In effect, cloud-RAN is a direct realization of CoMP. CoMP involves selecting cooperating clusters of antennas. Both the virtual controller and substrate controller have a role to play in this process. Having been assigned virtual antenna resources in a geographical area, the virtual controller is responsible for selecting appropriate clusters of antennas from the resources it is aware of to serve a particular user. If no sufficient clusters are available, the virtual controller may request additional antenna resources from the substrate controller. The substrate controller is then responsible for re-embedding the virtual network with extra virtual antenna resources, which are suitable for forming clusters in the desired area.

[196] analyses the interplay between spectrum and cloud-based antennas. The authors envision a scenario consisting of virtual network operators who bid for a combination of spectrum and antennas, which are partially substitutable. This vision is enabled by cloud-RAN, which permits antennas to be treated as virtual resources that can be allocated and shared among different operators. This trade-off in the system between using more antennas or more bandwidth is also considered in [197], which considers a cloud-RAN platform and the licensed shared access (LSA) spectrum sharing concept.

Multiple antenna techniques also have a role to play in dense small cell deployments. Small cell deployments are generally random with limited coordination, resulting in high inter-cell interference. In order to make small cell architectures feasible, it is necessary to introduce techniques such as CoMP that can mitigate this interference. In particular, CoMP has direct application in the device-centric architectures [6] described in Section III-C-1. Device-centric architectures consider the device to be the fundamental element in the cellular architecture and permit the user to connect to multiple small cells simultaneously. Techniques such as joint transmission and joint reception are designed for use in such a scenario.

V. Conclusion

Previous generations were designed in response to the killer applications of the time, comprised of specifically designed hardware optimized for a single purpose. The scenarios to be supported by 5G are too diverse and contrasting to be serviced efficiently by a single type of network. In addition, new technologies such as in-band full duplex, new waveforms, mmWave, and M-MIMO demonstrate clear heterogeneity in their capabilities, proving advantageous only in certain scenarios and not others. Instead, a change in the traditional design paradigm for networks is required. 5G needs to be adaptable, allowing a diverse range of technologies to be configured in order to satisfy a wide range of services.

In this paper, we examined how the new range of radio access technologies being considered for 5G can facilitate the creation of an adaptable 5G network. New advances in multiple antenna use, waveforms, and duplexing offer increased options to the network operator. Through reconfiguration, the radio access network can be dynamically tailored to meet the demands of the wide range of services targeted by 5G. The trend towards increased softwarization facilitates the concept of an adaptable and reconfigurable network, signifying a move away from the rigid networks of previous generations.

The interplay between the new set of radio access technologies and the emerging system-level techniques is of great importance in the pursuit of adaptable networks. System-level techniques such as cloud-RAN and software defined networking introduce higher levels of abstraction into the network, which brings an inherent increase in flexibility. Furthermore, in order to have a network that can support so many diverse services, it is necessary that network elements at all levels of abstraction can adapt harmoniously in a manner that complements and assists one another towards a common end goal. Hence, a tight coupling is required between radio access technologies and system-level techniques. Tools such as virtualization and cognitive networks can help bridge this relationship, enabling a high level of adaptability and configuration in 5G.

Currently, 5G just represents a collection of service requirements, concepts, and visions. What 5G will ultimately end up looking like is, thus far, unknown. The techniques mentioned in this paper, such as in-band full duplex, SDN, cloud-RAN, and virtualization, may or may not find their application in the next generation of mobile communications. However, regardless of its composition, it is clear that 5G will need to be versatile and adaptable. This paper surveys the potential for new technologies and techniques at various layers to contribute to the flexibility and adaptability of the network. In this regard, it serves as an overview of the choices and options afforded by new radio access technologies, and the manner in which adaptability can be achieved through interaction with system-level techniques.

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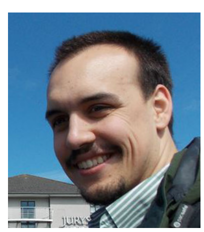

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