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INVITED PAPER

On the Flexibility and Autonomy of 5G Wireless Networks

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ABSTRACT With the emergence of the fifth generation (5G) wireless networks, not only is the increase in mobile broadband targeted, but also the support of various novel use cases, such as industrial automation, autonomous vehicles, e-health, and Internet of Things together with their requirements leading to highly heterogeneous wireless networks. This requires a re-design of the network architecture to ensure the coexistence of these use cases and guarantee user experience and service requirements. Therefore, 5G networks will be highly flexible and support online learning and autonomous decision making capabilities in a centralized and distributed manner to ensure highly efficient management of wireless and network resources. In this paper, the main features enabling flexibility and autonomy in 5G networks are discussed together with potential applications in different layers of the wireless network.

INDEX TERMS 5G, PHY and MAC design, low-latency, high-reliability.

I. INTRODUCTION

Wireless communications and networking have been evolving continuously over the last two decades and are essential parts of our lifestyle. This uninterrupted development is being carried out to improve the quality of services and applications supported by the wireless networking technology. Enormous efforts in cellular network research and development have been made to enhance the user quality of experience. In this context, the upcoming fifth generation (5G) of mobile communication networks will be challenged by the requirement of providing connectivity *everywhere* and at *any time* for various emerging use cases that exhibit diverse and (partly) competing requirements [1]. The Next Generation Mobile Networks (NGMN) agreed on the following 5G use case categories [2]:

- ''Enhanced mobile broadband (eMBB)'' addressing human-centric use cases for access to multimedia content, services, and data. In the eMBB category, the user experienced data rate - ranging from 100 Mbit/s up to 1 Gbit/s - is defined as the achievable data rate that is available ubiquitously across a considered target coverage area.
- ''Massive machine type communications (mMTC)'' are characterized by a very large number of connected devices that typically transmit a relatively low volume of non-delay-sensitive information. In the mMTC category, a high connection density (up to $10^6/\text{km}^2$), a very high link budget as well as a long battery life time are the most important requirements.
- ''Ultra-reliable-low-latency communications (URLLC)'' for use cases that have very strict requirements, especially in terms of end-to-end latency and/or reliability. For URLLC categories, low latency (in the millisecond range) and high reliability (99.999% and beyond) together with zero mobility interruption are of utmost importance. Important applications within the context of URLLC are, for example, a) fully automated vehicles and intelligent transport systems to achieve better traffic efficiency, to save time for other activities during driving, and to significantly reduce the number of traffic accidents, b) e-health and tele-surgery to offer medical support remotely and enable remote surgery, etc., and c) autonomous industry for efficient, flexible, and individual production of various products.

While some of these applications have stringent requirements on either latency or reliability, other applications require both simultaneously and/or require high data rates.

Since 5G networks will support simultaneously a variety of heterogeneous services with diverse quality of service (QoS), latency, and reliability requirements, 5G will ask for novel solutions to cope with these challenges. However, it will also provide tools to cope with these challenges, such as multi-radio access technology (multi-RAT) integration and a novel network architecture supporting softwarization and virtualization. Within this context, software-defined networking (SDN) is considered as a promising architecture to isolate the control plane and the use of a centralized network controller handling control plane functionalities, e.g., the allocation of traffic to network elements. Network intelligence, hereby, is centrally managed by the network controller and, thus, the network controller outputs the best fine granular flow routing control rules to the network devices based on its intelligent decisions. The virtualization of network functions provides the infrastructure on which SDN can run. It is a complementary technology of SDN which aims to (i) decouple the network functions from proprietary hardware appliances so they can run in software and (ii) consolidate many network equipment types onto industry standard high volume servers, switches and storage. Those tools provide flexibility in the architecture together with network orchestration capabilities to configure adaptively the appropriate subset of network nodes and resources for each use case and provide simultaneous support of multiple RATs. A multi-RAT system offers more resources which, in turn, can be used for diversity techniques to improve the reliability of the wireless connection. Nevertheless, resources in wireless networks are not infinite and require effective, self-organized management. Therefore, flexibility and self-organizational capabilities need to be supported in (almost) all layers of 5G wireless networks. With the advancements of the infrastructure technology for accommodating the next generation of networks and its flexible architecture, self-organizing capabilities will firmly be entrenched as the automation engine for wireless networks to drive the transformation of wireless networks towards 5G. Machine learning and autonomous decision making capabilities will enable 5G networks to be user- and service centric, so that 5G networks will not only be able to analyze available (network) data to guarantee QoS requirements but also to predict, recommend, and make automated decisions for delivering adaptively and intelligently the performance when and where needed.

Operators have come to realize that self-organization is now ready to take on the role of defining the future of automated operation in 5G wireless networks. User- and service centric self-organization will leverage centralized and hierarchical self-organizing network (SON) solutions to ensure the coexistence of various use cases with diverse requirements and to deliver superior performance for almost 100% user satisfaction. Therefore, 5G networks will not only support a flexible network architecture together with softwarization and virtualization, but also facilitate entities and functionalities for the support of learning and decision making within these entities together with required interfaces for information exchange and access.

In this paper, we first summarize the key features of 5G wireless networks leading to their flexible nature and enabling 5G networks to become highly autonomous. Hereby, we highlight the main approaches and definitions by standardization bodies on the 5G architecture, softwarization, virtualization, medium access control (MAC) and physical (PHY) layers. In addition, different diversity concepts are discussed that need to be supported by 5G networks to ensure the QoS of various use cases. Hereby, based on the channel conditions and the detailed application requirements, appropriate multi-connectivity variants and transmission schemes need to be selected and applied dynamically, such that the requirements are fulfilled with efficient resource usage. In addition to flexible resource management, the PHY functionalities should be adapted. Therefore, we envision a fully flexible PHY layer that can be reconfigured online to meet diverse, often conflicting, requirements. We embed the multi-carrier waveform into a general framework and identify necessary parameters which need to be reconfigured on-the-fly to meet the service requirements. We extend this idea to a fully adaptive reconfiguration that adapts the PHY parameters based on the current wireless characteristics, by employing model-based and machine-learning based link abstraction algorithms and identifying open research questions for a successful operation.

II. 5G NETWORKS AND ARCHITECTURE DESIGN

5G constitutes not only a new air interface but also a new generation of radio systems and network architecture, in which different radios (legacy and new) are expected to co-exist in an optimal manner [4]. Within the pioneering work of 5G communications networks, researchers consider a multi-dimensional performance metric cube aiming at extreme data rates, full coverage, low energy consumption, high reliability, low latency, etc., e.g., [2], [5], [6]. On the one hand, while high data rates can be achieved with millimeter wave frequencies, which provide bandwidths in the Giga Hertz range, these frequency bands may lead to high outages due to their propagation properties. On the other hand, high reliability can be achieved by, for example, retransmissions of the same data and an efficient combination of the retransmitted data at the receiver. However, this approach leads to increased latency. Another common technique for improving the reliability of a wireless transmission is diversity, e.g. the simultaneous transmission over multiple independent frequencies. However, in a multi-user network with limited frequency resources, transmission over multiple frequencies may lead to a 'waste' of resources, so that multiple mobile devices may experience a significant degradation in data rate. Hence, the target requirements in 5G networks are competing and require efficient, effective, and self-organized (autonomous) management of radio and network resources, which in turn, requires a flexible network architecture. Therefore, the NGMN alliance has introduced the concept of network slicing [1], whereby a slice comprises an appropriate subset of (virtual) network functions and (physical) resources to run these network functions, forming a complete instantiated logical network to meet certain network characteristics required by a certain service/use case.

Network slicing, allows networks to be logically separated, with each slice providing customized connectivity for one service, and all slices running on the same shared infrastructure. This is a much more flexible solution than a single physical network providing a maximum level of connectivity as supported by today's networks. To serve a diverse ecosystem, such as the one considered for 5G, network orchestration functions will be deployed that will allocate appropriate computing and network resources to the services. Such orchestration functions target the on-demand management of diverse and dedicated network slices containing specialized networking and computing capabilities, which are expected to meet the desired service requirements of each 5G use case. In order to achieve the required agility for configuring on-demand digital services, the networks will be virtualized. Hereby, network function virtualization (NFV) and software defined networking (SDN) are the key technologies that make network slicing possible.

A. SDN AND NFV

As 5G networks promise increased wireless capacity and speed with reduced latency and improved reliability, the SDN architecture can help to maintain the variety of devices and use cases and to improve the performance and scalability. SDN has emerged as a new intelligent architecture for network programmability. As defined by the Open Networking Foundation (ONF), the SDN architecture ''decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services''. The decoupling of the control plane and data plane in an SDN environment leads to the following: The control plane is mostly responsible for making decisions on how packets are forwarded by one or more network resources and pushing such decisions down to the network resources for execution, i.e. the control plane acts as a single, logically centralized network operating system in terms of both scheduling and resolving resource conflicts. The data plane, which is also known as the forwarding plane, forwards the traffic to the selected destination according to the control plane logic. In addition to the control and data plane, there is the management plane which is mostly responsible for monitoring, configuring, and maintaining network devices, e.g. making decisions regarding the state of network resources.

Besides ONF, multiple other standardization bodies have contributed to the SDN standardization. These bodies are I) the International Telecommunication Union (ITU) [7], II) the Internet Engineering Task Force (IETF) [8], and III) the European Telecommunications Standards Institute (ETSI) [3]. Their focus are on i) definition and interoperability (ITU-T), ii) general standards, perspectives, and use cases (IETF), and iii) framework and requirements (ETSI), respectively. Hereby, SDN is defined ''as a set of techniques that enables to directly program, orchestrate, control, and manage network resources, which facilitates the design, delivery, and operation of network services in a dynamic and scalable manner'' [9]. This leads to the fact that the network intelligence is (logically) centralized in software-based SDN control functions that maintain a global view of the network, which appears to applications and policy engines as a single, logical switch. This intelligence is located in dedicated network elements, namely SDN controllers. Hence, SDN uses centralized intelligence to manage and push policy for all parts of the network, so that networks can be built and changed centrally, rather than requiring network managers hopping from device to device to make changes manually, which leads to greater efficiency in the network.

With the virtualization of network functions, a dynamic construction and management of network functions and their relationships regarding their associated data, control, management, and dependencies are enabled. NFV essentially decouples network functions from the underlying physical hardware infrastructure, so that any network functionality can run on general purpose computing servers with improved operational efficiency resulting from common automation and operating procedures. This allows a flexible (re-)allocation of sets of network resources (network slices) to support specific 5G applications as well as the isolation between such slices. Hence, NFV is a promising concept for realizing different 5G applications that exhibit diverse and competing requirements while still using the same wireless network infrastructure [11]–[13]. Since NFV together with (virtualized) network services did not exist previously, the handling requires a new and different set of management and orchestration (MANO) functions which are located in the NFV-MANO entity in emerging 5G networks.

B. MANAGEMENT AND ORCHESTRATION

5G networks will integrate existing RATs together with emerging new radios for improved service coverage and optimum resource usage. The flexibility and the highly integrated nature of 5G networks will bring a level of complexity that can be mastered only by virtualization. Hereby, automated operation and intelligence is anticipated to be applied to the virtualized networks, the management of radio and energy resources in a multi-RAT, multi-service system, and ultimately to the optimization of service provisioning and user experience.

The programmability of the infrastructure is the enabler for the end-to-end management and orchestration of resources and services. As stated above, the decoupling of software implementations of network functions from the computation, storage, and networking resources exposes a new set of entities, i.e. the Virtualized Network Functions (VNFs)

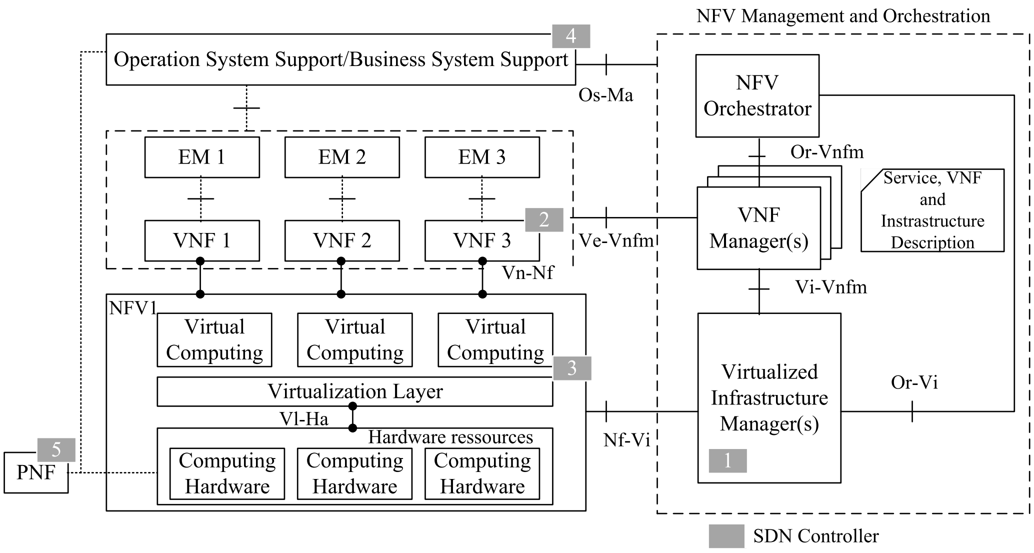

FIGURE 1. The NFV-MANO architectural framework with reference points and potential SDN controller positions [3].

and a new set of relationships between them and the NFV Instrastructure (NFVI). The dynamic management of the NFVI and the orchestration of the resource allocation needed by the network service and the VNFs are handled by the NFV-MANO entity. An illustration of the architectural framework of the NFV-MANO together with the potential location of SDN controllers which are essential for the flow control management and for realizing *intelligent* networks is depicted in Fig.1. Hereby, the NFV-MANO functional blocks consist of the Virtualized Infrastructure Manager (VIM), the NFV orchestrator, and the VNF manager. Further functional blocks sharing reference points (i.e. Os-Ma, Ve-Vnfm, NF-Vi, Or-Vi, Vi-Vnfm, Or-Vnfm, Vn-Nf) with the NFV-MANO are the Element Management (EM), VNFs, Operation System Support (OSS) and Business System support (BSS) functions, and the NFVI. As depicted, the SDN controllers can be merged with the VIM functionality (location 1), be virtualized as a VNF (location 2), be part of the NFVI (location 3), can be part of the OSS/BSS (location 4), or can be a Physical Network Function (PNF) (location 5). Given the fact that a SDN controller can run different (machine learning based) algorithms, the intelligence of the network is, hence, represented by and located in several entities.

C. 5G ARCHITECTURE

To meet the demands of the emerging use cases and to overcome the challenges that have been put forward in the 5G system a drastic change in the strategy of designing the 5G wireless cellular architecture is needed. Therefore, a new architecture has been discussed by NGMN which is able to manage complex multi-layer and multi-technology networks, and to achieve built-in flexibility requiring an intelligent management and orchestration so that the 5G networks will be cognitive and optimize themselves autonomously. Cognitive networks will use big data analytics and artificial intelligence/machine learning tools to setup a logical network for various use cases and to solve complex optimization tasks in real time and in a predictable manner.

Since not all use cases require the same performance and functionality, 5G moves away from a monolithic design and includes by design embedded flexibility and scalability of capabilities, to enable a wide range of use cases and to facilitate innovation through various business and partnership models. Therefore, the NGMN alliance has proposed design principles for the 5G architecture enabling the operator to configure the data flow to be used on demand only and in a programmable manner and to configure necessary functions in the network in order to optimize operational and management costs [1]. These design principles have been further detailed by 3GPP in [4] and [14]. In order to assure maximum flexibility and scalability during the technology lifecycle, the 5G system design should, according to NGMN, adopt functional split of network domains as well as network elements such that i) the core network and radio access network (RAN) are functionally decoupled, ii) SDN and NFV are supported, iii) changes to one network domain should not mandate changes to other network domains, and iv) real-time and on-demand network configuration and automated optimization should provide flexible and cost efficient network operation, such that autonomic/self-management functions shall be provided both at the management plane and at the control plane level and shall support a flexible architecture.

Finally, to support multiple use cases simultaneously [15], NGMN introduced the concept of network slicing [16] according to which the 5G network architecture is composed of multiple slices. The concept of network slicing has the advantage of enabling the 5G system to confine service-specific security/assurance requirements to a single slice, rather than the whole network. The dynamic creation of

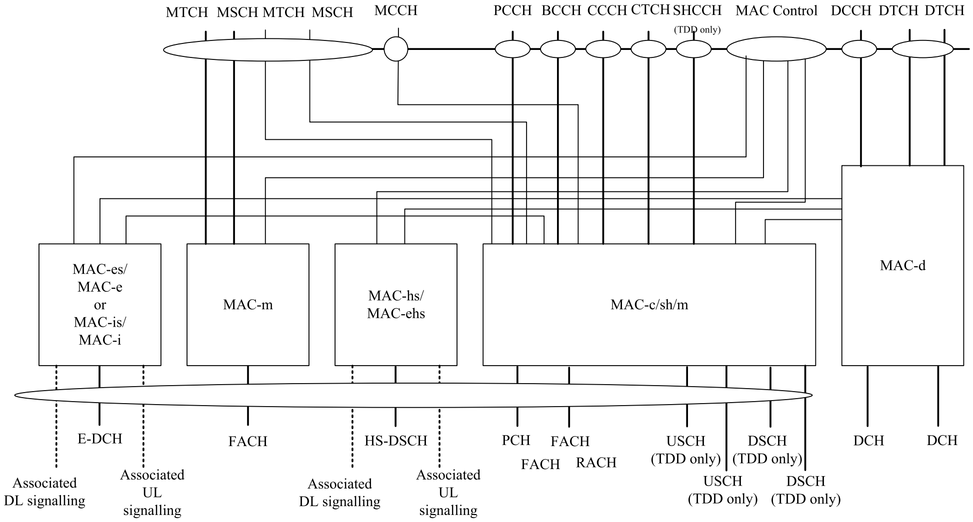

FIGURE 2. Illustration of the user-side MAC architecture [10].

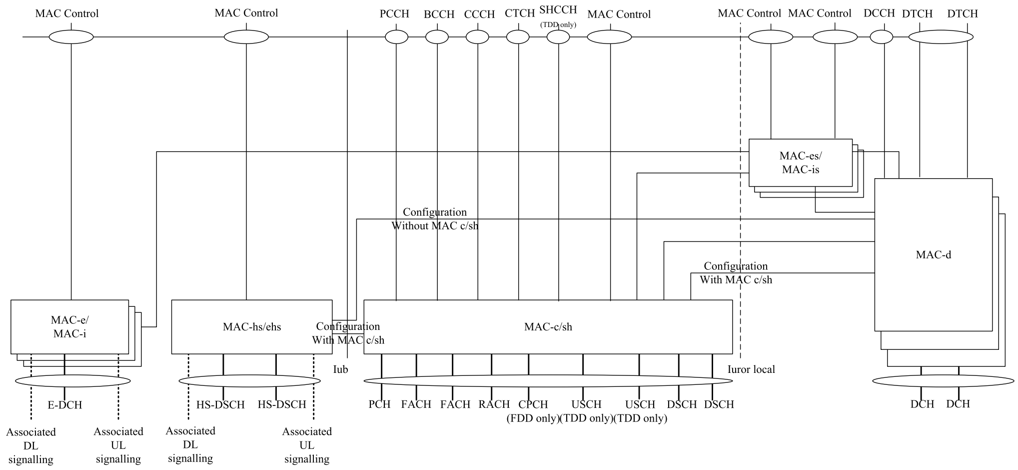

FIGURE 3. Illustration of the 5G RAN-side MAC architecture [10].

a network slice by an operator to form a complete fully operational network requires autonomous decision and learning capabilities which need to be supported by the end-to-end management and orchestration entity of 5G networks. Hence, in order to maximize utilization efficiency of available network resources, it should be possible to relocate network resources dynamically and flexibly depending on current and local needs, under full control of the operator by using tool such as autonomous decision making or machine learning.

III. MAC ARCHITECTURE AND MAC ENTITIES OF 5G NETWORKS

3GPP describes a MAC architecture model together with the MAC entities and MAC functions for release 14 in [10], which does not specify or restrict any implementations. Hereby, two 5G-MAC entities are defined; one in the user and one in the 5G-RAN. These 5G-MAC entities handle the various transport channels, i.e. 5G Broadcast Channel (xBCH); 5G Downlink Shared Channel(s) (xDL-SCH); 5G Uplink Shared Channel(s) (xUL-SCH); 5G Random Access Channel(s) (xRACH). A traffic related MAC architecture from the user side and from the 5G RAN side is considered as illustrated in Fig. 2 and Fig. 3, respectively. The MAC architecture is constructed by the following MAC entities which have different functions when completed by the user than when completed by the 5G-RAN:

- **MAC-b**: the MAC entity that handles the Broadcast Channel (BCH)
- **MAC-c/sh/m**: the MAC entity that handles the following transport channels:
  - Paging Channel (PCH)
  - Forward Access Channel (FACH)
  - Random Access Channel (RACH)
  - Downlink Shared Channel (DSCH), which exists only in Time Division Duplex (TDD) mode.

  - Uplink Shared Channel (USCH), which exists only in TDD mode.
- **MAC-d**: the MAC entity that handles the Dedicated Transport Channel (DCH)
- **MAC-hs/ehs**: the MAC entity that handles the High Speed Downlink Shared Channel (HS-DSCH)
- **MAC-m**: the MAC entity that handles the Forward Access Channel (FACH)
- **MAC-e/es and MAC-i/is**: the MAC entities that handle the Enhanced Dedicated Transport Channel (E-DCH)

Fig. 2, depicts the connectivity of the MAC entities for the traffic related architecture from the user side. It is shown which entity controls the access to which transport/dedicated channel. The associated signalling shown in the figure illustrates the exchange of information between layer 1 and layer 2. Similarly, Fig. 3, depicts the connectivity of the MAC entities for the traffic related architecture from the RAN side. The MAC control may carry uplink control information or scheduling information, respectively.

The 5G MAC layer provides services to the upper layers like data transfer and radio resource allocation while expects services from the physical layer such as data transfer services, signalling of HARQ feedback, signalling of scheduling requests, and measurements (e.g. channel quality information or beam information) [17]. In addition, the 5G MAC layer provides functions such as mapping between logical channels and transport channels, (de-)multiplexing, scheduling information reporting, error correction through HARQ, beam management, priority handling between users and logical channels, logical channel prioritization, and transport format selection. Furthermore, 3GPP considers the case that a user might be assigned to multiple cells simultaneously. Thereby, the MAC controls the user's access to various transport channels, e.g. FACH. This enables the MAC layer to perform multi-connectivity and control the multiple wireless links assigned to one user, which is further detailed in Sec. IV. Given the heterogeneous and dynamic nature of 5G networks, all these functions and decisions have to be performed in an autonomous and intelligent manner at the MAC layer, either in a centralized way or in a distributed way where each node makes its own decisions.

All these features and because the MAC layer is an intermediate layer between the PHY layer and the upper layers, leads to challenges in the MAC layer design and functions. One such challenge is to cope with the dynamics and design features of these layers. 5G is expected to support multiple RATs, which requires the MAC to support an entirely new mapping functionality between (logical and transport) channels, priority handling, and scheduling functions which are RAT-specific in nature. Especially, in case of multi-connectivity with transmission over different cells at different RATs novel scheduling algorithms need to be designed. One such algorithm might be a RAT-aware scheduler in both time- and frequency domain.

IV. FLEXIBLE MANAGEMENT OF DIVERSITY

Given the flexibility and self-organizing capabilities of 5G networks, various diversity techniques can be adaptively applied to fulfill the challenging application requirements regarding reliability, latency, and throughput.

A. DIVERSITY TYPES

Wireless connectivity can be interrupted by various events ranging from power outages and drastic channel fades to software bugs and misconfiguration; nonetheless, predominantly, the wireless channel is a major source of failure. Effects such as small- and large-scale fading lead to variations of the wireless channel and potential outages. A widely accepted way to compensate for such effects is diversity. *Spatial* microdiversity in form of multiple antennas at the transmitter and/or receiver is regarded as an effective tool to combat small-scale fading and enhance the reliability performance. Results in [18]–[20] demonstrate that using more antennas has a significant impact on the reliability of wireless transmissions. Furthermore, macrodiversity, i.e., multiple transmissions from or to locations that are separated by much more than the wave length used, is appropriate to combat large-scale fading effects such as shadowing. Frequently, connectivity between a UE and multiple BSs is referred to as multi-connectivity. If the communication happens at the same carrier frequency, such a setup is also called intra-frequency multi-connectivity. Established principles in this regard are Single Frequency Network (SFN) [21] and Coordinated Multi-Point (CoMP) [22], [23].

Another diversity type is *frequency* diversity. Two signals whose frequencies are separated by at least the coherence bandwidth experience approximately uncorrelated small-scale fading [24]. A setup where multiple transmissions on different carrier frequencies are used to transfer the same data is termed inter-frequency multi-connectivity. In LTE, such concepts are already implemented for increasing throughput and capacity. Carrier Aggregation (CA) [25] is used to bundle several component carriers to a virtual larger band. CA is implemented at MAC layer and requires tight synchronization; thus, it is typically limited to collocated deployments. In LTE Release 12, Dual Connectivity (DC) [26] was introduced to combine two carriers at a higher layer, namely Packet Data Convergence Protocol (PDCP) layer, which leads to relaxed synchronization and scheduling requirements and is supported also in non-collocated deployments. It is foreseen to extend DC to more than two carriers in 5G [27].

In addition, diversity can be also achieved by multiple transmissions in *time*. If a transmission fails, the data is retransmitted until it is received successfully. Combining retransmissions with coding schemes such as Chase Combining or Incremental Redundancy represents a powerful way of exploiting time diversity and realizing link adaptation.

B. REDUCTION OF LATENCY

In general, URLLC applications require significantly reduced latency compared to what is provided by today's wireless technologies. Various techniques are currently discussed to reduce latency. The Transmission Time Interval (TTI) needs to be reduced from 1 ms to 0.1–0.25 ms or below [14]. In this context, it is important that the PHY flexibly supports such low latencies in combination with transmissions of applications that have different requirements, e.g., high throughput, see Sec. V.

Other examples of latency improvements that are currently developed are semi-persistent scheduling to accelerate the uplink channel access [14], [28] and D2D communication to enable direct communication among UEs [18]. Furthermore, an adaptive network management with SDN and NFV helps reducing routing paths and reconfiguration delays in case of failures and network changes, see Sec. II.

Another important aspect is the number of retransmissions that is allowed by the application requirements. In [19], [29], and [30], the benefits of Hybrid Automatic Repeat Request (HARQ) regarding the reliability performance are discussed and evaluated. Due to the low latency requirements, the number of retransmissions is typically limited to at maximum one, even better to zero [30]. Moreover, the impact of HARQ on the reliability performance is limited in case of very short latency requirements [31]. One reason is that the coherence times of the wireless channels are typically longer than the latency requirements diminishing diversity gains of retransmissions. Due to the same reasons, the benefits of opportunistic scheduling are expected to be negligible too. Owing to the hard real-time requirements of URLLC applications, it is not possible to delay data transmissions in case of bad channel conditions. In contrast, other 5G applications that have moderate latency requirements may benefit to a greater extent from time diversity. All in all, a flexible management is needed that adapts the use of time diversity to the detailed application requirements. In case of very stringent latency requirements, space and frequency diversity need to be exploited instead of time diversity.

C. MULTI-CONNECTIVITY FOR ENHANCED RELIABILITY

In 5G, multi-connectivity can be also utilized for enhancing the reliability of wireless transmissions. Intra-frequency multi-connectivity techniques such as SFN or CoMP are used to enhance the signal quality and increase the probability of successful data transmissions. In case of inter-frequency multi-connectivity, packet duplication across the radio interfaces is used instead of splitting the data, as done in CA and DC [27], [32]. Again, various functional splits with distinct properties are possible, see [32], [33]. Lower layer integration of inter-frequency multi-connectivity (similar to CA) exhibits increased complexity but also enables tight coordination, which is beneficial for low latency applications. In contrast, higher layer integration (similar to DC) enables to fully exploit the capabilities of the individual connections because there are fewer coordination constraints. In essence, various splits are possible and adaptive techniques following the SDN/NFV concepts are needed to adapt the multi-connectivity configuration to the applications' needs and channel conditions and to optimize the resource use across the network. To elaborate, resources of multiple RATs, BSs, network layers, and carrier frequencies need to be aggregated and managed such that the various application requirements are satisfied. Some first research results on intra- and inter-frequency multi-connectivity can be found in [34] and [35], respectively. The results show that a flexible management of space, frequency, and time diversity is required to efficiently exploit the available resources and trade-off reliability and latency requirements.

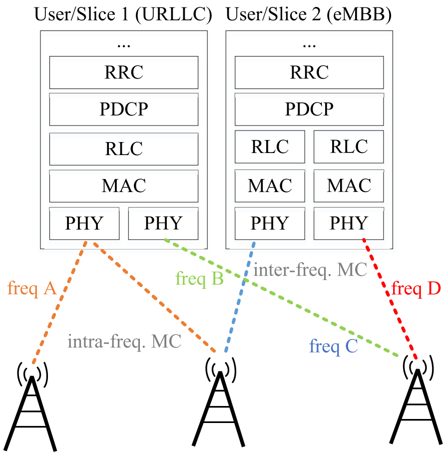

FIGURE 4. Flexible adaption of multi-connectivity types and functional splits for supporting diverse use cases.

An example illustrating the presented ideas is shown in Fig. 4. User/slice 1 requires support of a URLLC application while user/slice 2 focuses on achieving high throughput for an eMBB application. To satisfy the needs, the network management adapts the multi-connectivity setup accordingly, i.e., lower and higher layer combining are configured for users/slices 1 and 2, respectively. Moreover, in addition to inter-frequency multi-connectivity, which is configured for both users/slices, the transmission on frequency A is improved by utilizing intra-frequency multi-connectivity of the left and middle BSs. This example illustrates how multi-connectivity and functional splits can be flexibly adapted in self-organized 5G networks with diverse service classes and network slices.

V. EXTENSION OF THE SOFTWARE-BASED CONCEPTS TO THE PHYSICAL LAYER (PHY)

Driven by the virtualization and abstraction of the network structure by SDN and NFV, it is a logical step forward to also provide a software defined waveform (SDW) on the PHY which can be reconfigured online via software to meet the requirements imposed by the network slice. This demands a flexible PHY technique which is capable of addressing all requirements, though not all at the same time. Moreover, an intelligent approach to harness this flexibility for addressing diverse applications in an efficient manner is necessary.

A. MULTICARRIER WAVEFORMS

4G PHY is based on the orthogonal waveform orthogonal frequency division multiplexing (OFDM). Its orthogonality has eased the PHY implementation, particularly in multipath fading channels and when combining with MIMO techniques. However, it limits the design space of the waveform. Namely, to preserve the orthogonality in a doubly dispersive channel, the OFDM symbol needs to have a cyclic prefix (CP) with length larger than the maximum channel delay spread, while the symbol duration must be smaller than the coherence time of the channel. Furthermore, to have a block-based structure, the discontinuity between OFDM symbols causes high out-of-band (OOB) emission.

In 5G, to improve the OOB performance of OFDM, subband filtering and time-domain windowing have been proposed to be applied on top of OFDM. The resulting waveforms, i.e., filtered OFDM [36], universal filtered OFDM [37] and OFDM with weighted overlap and add (WOLA) [38], become quasi-orthogonal. Furthermore, alternatives to OFDM-based waveforms have been proposed. Abandoning the block-based structure, filter-bank multicarrier (FBMC) [39] can achieve ultra-low OOB emission. But, due to the use of a long linear filter, it is not suitable for burst transmission. Applying circular filtering rather than linear filtering, the waveform termed windowed CP circular offset QAM (WCP-COQAM) [40] preserves the block-structure at the cost of an increased OOB emission compared to FBMC. 4G DFT spreading OFDM (DFT-s-OFDM) allows multiuser uplink with low PAPR, but at the cost of increased receiver complexity and problematic application of MIMO techniques. F-OFDM achieves low OOB emission, however at the cost of interblock-interference and therefore reduced throughput. In [41], we have provided an extensive comparison of the link level performance achieved by the advanced multicarrier waveforms that are being intensively researched as alternatives to OFDM for 5G systems and beyond. The results indicate that each waveform proves to be advantageous in different application scenarios and there is no ultimate waveform that is equally suitable for all requirements. As a consequence, a unification of diverse waveforms into a common framework leads to the possibility of configuring the PHY layer by a simple change of waveform parameters, which can be done in an online fashion.

B. GABOR FRAMEWORK AND GENERALIZED FREQUENCY DIVISION MULTIPLEXING (GFDM)

As a common property of all modern waveforms, complex-valued data is transmitted on resources that are distributed in a 2-dimensional grid among time and frequency. Additionally in block-based, cyclic waveforms, blocks are separated by a CP; continuous waveforms can be understood as overlapping blocks of block-based waveforms, where the CP has been omitted. In mathematics, Gabor theory analyzes the distribution of data through time and frequency using some prototype filter. Its fundamental operations are Gabor expansion and Gabor transform, and we can identify the transmission of a multicarrier waveform as a Gabor expansion, whereas the linear demodulation is described by a Gabor transform. Hence, the Gabor theory suits perfectly as a common mathematical framework for multicarrier waveforms. The multicarrier waveform termed Generalized frequency division multiplexing (GFDM) [42] directly implements these operations in the discrete domain and can therefore serve as a reconfigurable system. By being able to emulate various waveforms, their specific advantages can be exploited for different application scenarios.

In a general block-based multicarrier framework, in one block, we assume M subsymbols to be distributed in time domain and K subcarriers to be distributed in frequency domain. In addition, each data symbol is transmitted on a waveform that is concentrated at a certain subsymbol and subcarrier. The critical density of packing the symbols with no ambiguity into the block is reached, when the subcarrier spacing $\Delta_f = \frac{\nu_{\mathrm{f}}}{\Delta_t}$, where Δ_t is the subsymbol spacing and $\nu_{\mathrm{f}} = 1$ is the frequency spreading factor. Upon insertion of a CP between blocks, all block-based waveforms can be modeled by this framework. When introducing the notion of empty subsymbols (i.e. they transmit the value "0"), this model can be extended to emulate continuous waveforms such as FBMC by leaving subsymbols empty and overlapping the blocks.

Based on this notation, we will illustrate how the different waveforms fit into the Gabor theory and how GFDM is to be configured to yield different waveform types. The general configuration parameters are shown in Table 1, where the notation M_s denotes the amount of zero-valued subsymbols and M_p is the filter length relative to the subsymbol spacing. The different waveforms are characterized by two aspects. First, the parameters related to the dimensions of the underlying time-frequency resource grid for a single block are explored. This includes the number of subcarriers K and subsymbols M in the system. The scaling factor in frequency ν_{f} can theoretically take values of any rational number larger than zero, while $\nu_{\mathrm{f}} = 1$ relates to critically sampled Gabor frames and hence a non-ambiguous transmission of maximum spectral efficiency. The second set of features is related to the properties of the signal. Here, the choice of the pulse shaping filter is a significant attribute. Moreover, the use of OQAM is needed for some waveforms, aiming to achieve higher flexibility. Further, some waveforms rely on a CP to allow transmission of a block based frame structure in a time dispersive channel, while others do not use CP in order to achieve higher spectrum efficiency.

1) CLASSICAL WAVEFORMS

The family of *classical waveforms* includes OFDM, block OFDM [43], single-carrier frequency domain equalization (SC-FDE) and single-carrier frequency domain

TABLE 1. GFDM as a software-defined waveform.

design space	GFDM	CP-OFDM	block OFDM	SC-FDE	SC-FDM	FBMC OQAM	FBMC FMT	FBMC COQAM	CB-FMT
# subcarriers	K	K	K	1	K	K	K	K	K
# subsymbols	M	1	M	M	M	M	M	M	M
scaling freq.	ν_f	1	1	1	1	1	> 1	1	> 1
silent subsym.	M_s	-	-	-	-	M_p	M_p	-	-
filter imp. resp.	general	rect	rect	Dirichlet	Dirichlet	$\sqrt{\text{Nyquist}}$	$\sqrt{\text{Nyquist}}$	$\sqrt{\text{Nyquist}}$	general
offset mod.	(yes)	no	no	no	no	yes	no	yes	no
cyclic prefix	yes	yes	yes	yes	yes	no	no	yes	yes

multiplexing (SC-FDM). Particularly OFDM and SC-FDM have been relevant for the development of the 4G cellular standard LTE. All four waveforms in this category have in common that $\nu_\mathrm{f} = 1$, which allows to meet the Nyquist criterion. Silent subsymbols are not employed, the CP and regular QAM are used used in the default configuration. OFDM and block OFDM fit into the framework of Gabor theory, where a rectangular prototype filter is used. Additionally, OFDM is restricted to one subsymbol, while block OFDM constitutes the concatenation of multiple OFDM symbols in time to create a block with a single common CP. Similarly, SC-FDE and SC-FDM fall into the framework of Gabor expansion and transform, when the prototype pulse is a Dirichlet kernel and, analogously, the number of subcarriers in SC-FDE is $K = 1$, while SC-FDM is a concatenation in frequency of multiple SC-FDE signals.

2) FILTER BANK WAVEFORMS

The family of *filter bank waveforms* evolves around filtering the subcarriers in the system and still retaining orthogonality. As the names suggest, FBMC-OQAM [44] and its cyclic extension FBMC-COQAM [40] rely on offset modulation, while in FBMC-frequency multi-tone (FMT) and cyclic block filtered multitone (CB-FMT) [45] the spacing between the subcarriers is increased such that they do not overlap, i.e. $\nu_\mathrm{f} > 1$. In the context of block-based versus continuous waveforms, silent subsymbols become relevant. By switching off M_p subsymbols at the block edge, omitting a CP and overlapping subsequent blocks at the transmitter side, a continuous transmission is emulated. The FBMC techniques have in common, that an orthogonal transmission is achieved, either by sacrificing spectral efficiency (FBMC-FMT) or accepting real-only orthogonality by employing the Offset-QAM modulation. However, the orthogonality in OQAM breaks as soon as the wireless channel becomes frequency-selective.

Even though subband filtered waveforms like UF-OFDM and F-OFDM do not fall into the classical framework of Gabor expansion and transform, they can still be considered a concatenation of a classical system with a subsequent subband filtering stage. Therefore, they can be readily included into a PHY virtualization.

C. PHY ABSTRACTION FOR LINK ADAPTATION

The PHY layer abstraction aims at developing a simple and accurate model to predict the link-level performance. It not only assists the system-level simulation and but also is needed for designing link adaptation strategies, such as adaptive modulation and coding (AMC), power allocation and MIMO switching.

The conventional way of PHY abstraction can be summarized into two steps, namely, i) using one parameter to quantify the link quality and ii) linking it to the probability of an erroneous decoding event, e.g., packet error rate (PER). Considering an OFDM-based transmission, each codeword can occupy multiple subcarriers and/or multiple time slots. Under a doubly-dispersive fading channel, the frequency- and time-dependent channel coefficients yield a set of diverse signal-to-noise-plus-interference ratios (SINRs). Techniques existing in the literature mainly rely on an estimate of the average SINR followed by mapping the so called effective SINR to a pre-calculated PER. Mathematically, we can compactly describe the generation of the effective SINR as follows

$$\mathrm{SINR}_\mathrm{eff} = \Phi^{-1}\left[\frac{1}{N}\sum_{n=1}^{N}\Phi(\mathrm{SINR}_n)\right], \tag{1}$$

where SINR_n stands for the SINR experienced by the data symbol n and N denotes the total number of data symbols per packet. The definition of the effective SINR mapping (ESM) function $\Phi(\cdot)$ can be done in various ways, e.g., by means of mutual information or bounds on the error probability. For more details, we refer the readers to [46]. Apart from being simple and accurate, the PHY abstraction techniques shall also be extensible to cope with the changes that are taking place in the development of the 5G network. In the sequel, we list three of them that may challenge the conventional way of PHY abstraction.

Firstly, MIMO techniques are playing more and more critical roles in achieving high spectral efficiency, delivering massive machine connectivity and enabling URLLC. With the number of antennas ranging from one up to several hundreds, the effective SINR shall capture the link qualities not only from the temporal and spectral dimensions, but also from the spatial dimension. In the literature, the single effective SINR based PHY abstraction has been shown to be inadequate for accurately predicting the link-level performance. For this reason, the link adaptation strategies developed on top of it are often suboptimal. For instance, Daniels *et al.* [47] showed the exponential ESM-based AMC has an appreciable performance gap to the optimal case in a 2×2 MIMO-OFDM system. In [48], the proposed criterion for effective MIMO mode switching was based on a vector of SINRs rather than a single one.

Secondly, to further improve the spectral efficiency and increase the system throughput, non-orthogonal multiple access schemes are being considered in 5G [49]. The users are no longer allocated with orthogonal communication resources. The presence of inter-user interference complicates the estimation of SINRs for PHY abstraction. Moreover, its impact on the link-level performance is dependent of the receiver. With the development of hardware technologies, near-optimal non-linear advanced signal processing techniques are becoming affordable at the receiver for separating superimposed user messages. Together with the non-linear distortion introduced by an imperfect radio front-end, this can make the link-level performance analysis intractable.

Thirdly, the heterogeneous nature of the 5G network results in more complex interference models. Even the common assumption that the interference follows a Gaussian distribution may no longer be valid under certain circumstances. For instance, a new type of modulation termed FQAM, a combination of Frequency Shift Keying (FSK) and Quadrature Amplitude Modulation (QAM), was proposed in [50] to improve the transmission rates particularly for the cell-edge users. The resulting statistical distribution of the inter-cell interference tends to be non-Gaussian.

Considering the above mentioned problems, we shall improve the PHY abstraction approaches from two aspects in order to keep pace with the development of 5G. One is to enlarge the feature space for characterizing the link quality. The other is to find link adaptation approaches, relying on fewer assumptions on the implementation of PHY and being versatile to the interference models.

D. MACHINE LEARNING FOR PHY ADAPTATION

In the past few decades, machine learning has been making big progresses in many fields. Its capability of learning from and making predictions based on data rather than on model assumptions and approximations makes it an attractive solution to analytically intractable problems. For our link adaptation problem on the PHY, there have been several attempts made in the literature that adopt machine learning techniques. Starting from the supervised learning based approaches, e.g., [47], [51], [52], they are provided with training data and typically consist of two steps. In the first step, we define the feature space made of measures that are not only sufficient but also necessary to characterize the link quality. Considering a MIMO-OFDM WiFi system, Daniels *et al.* [47], [52] have constructed the feature space by ordering the post-processing SNRs and selecting up to 4 elements that are the most relevant link-level performance indicators. The second step identifies a mapping function between the feature set and the link configuration to fulfill the design objective. Treating this task as a classification problem, both the k-nearest neighbor (kNN) and support vector machine (SVM) algorithms are usable and have already been adopted in [47] and [52]–[54]. To ensure that the classifier can adapt to the changes of the communication environment, Daniels *et al.* [52] extended their approach by exploiting the automatic repeat-request (ARQ) mechanism to real-time update the training data. The resulting on-line kNN classifier developed in [55] and also the SVM based version introduced in [56] and [57] formed the basis of an on-line learning framework for link adaptation. With the same design goal, Leite *et al.* [58] adopted the reinforcement learning framework and resorted to the Markov decision processes due to their successful application in cognitive radios.

Although the above-mentioned machine learning based link adaptation approaches have shown their competences against the conventional ESM-based ones, there still remain issues to be addressed in future works. First, the proposals have only been investigated in relatively simple systems, i.e. with an orthogonal waveform with only one or two antennas. The design space for link adaptation is still small, e.g., less than 20 supported modulation and coding schemes (MCSs). The consideration of the single-user scenario significantly simplifies the interference models as well. Second, even with such simple systems, several aspects of the machine learning algorithms need to be improved. So far, the construction of the feature set lacks a systematic and efficient approach. The memory has been an issue for training the classifier and updating it in a real-time manner. Last but not least, the convergence rate of on-line learning needs to be further accelerated for addressing a dynamic environment and burst communication.

E. SUMMARY AND CHALLENGES ON THE PHY DESIGN

In terms of system evolution, OFDM and its simple variants are a natural choice by 3GPP for intermediary standards and early releases of 5G systems. Nevertheless, non-orthogonal waveforms, i.e. GFDM and FBMC, are definitely worth investigation. In particular, the large design space of GFDM can be an enabler for a flexible PHY implementation. On top of it, we can effectively and efficiently harness the benefits provided by context-aware PHY configuration. The context information and the mapping to an optimized PHY configuration can be obtained by machine learning techniques. To this end, we are facing with a number of challenges on the PHY design. In the following, some of them are listed:

Firstly, it is known that energy efficiency and programmability are trade-offs in implementation. Even though hardware technologies are making great progresses, it is still a challenging task to realize a single PHY on hardware that can address a wide range of 5G applications while fulfilling the energy consumption constraint.

Secondly, the requirements of 5G applications are diverse. To address them, a mixed of numerologies is foreseen. This creates inter-numerology interference. In addition, asynchronous multiple accesses desired for energy efficiency and massive connectivity experience inter-symbol and inter-carrier interference. The inter-antenna interference becomes more severe as the number of antennas increases.

Overall, the wireless communication takes places in an interference-rich environment. To limit the negative impacts from different types of interferences, it is important to improve the spectral and temporal efficiency of waveforms. At the same time, advanced signal processing techniques are needed for resolving the interferences and recovering the useful information with an acceptable reliability.

Thirdly, 5G applications also present challenging communication channels. For instance, in the context of vehicular communication, the channel can be highly selective both in time and frequency. It is a critical task to estimate and track the fast varying channel state information without considerably reducing the spectral and temporal efficiency. For use cases related to communication support for vehicle automation, they have very stringent requirements on the reliability of wireless transmission. An accurate channel knowledge attainable at the receiver is an inevitable premise.

Another example is providing economically feasible wireless regional area network (WRAN) operation mode to deliver the service in remote area. The large cell in remote areas presents unique channel conditions. A long CP is needed for coping with the large channel delay spread. To mitigate the CP overhead, the symbol duration has to increase accordingly, making the transmission vulnerable to time-varying channels and synchronization errors. Unlike OOB emission reduction, simple filtering or windowing on top of CP-OFDM is inadequate to address this issue.

Concluding from above, advances in signal processing and energy-efficient implementation are an enabler of PHY innovations in the evolution of mobile communication systems.

VI. CONCLUSION

In this article, the key aspects related to the flexibility of 5G networks starting from the flexible architecture, SDN and NFV capabilities of 5G networks over to the MAC and the PHY layer design aspects are presented. Given the highly flexible nature of 5G networks as discussed and agreed by various standardization bodies and alliances, such as 3GPP, ETSI, and NGMN, 5G networks will be able to support highly autonomous and smart decision making capabilities at various layers of the network, including the PHY and MAC layers. Therefore, the SON and (radio) resource management functionalities will be not only located in a centralized entity but rather split so that some machine learning and decision making is performed centralized whereas others are performed distributed in different nodes. Therefore, we envision a fully flexible PHY layer that can be reconfigured online and adaptively to meet diverse requirements and a fully flexible MAC layer that adaptively performs user- and use case specific resource management.

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