Slice-aware 5G Dynamic Small Cells

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***Abstract*—Network Slicing has become one of the fundamental pillars of the fifth generation (5G) mobile and wireless communications systems, which promises integration of a plethora of new vertical industries with tailored network design. To this end, 3rd generation partnership project (3GPP) Release 15 has provided the basis of the network slicing support including radio access network (RAN). Nevertheless, for the realization of native end-to-end (E2E) network slicing, further features and optimizations shall still be introduced. This paper places the focus on enabling network slicing operation in small cell deployments. In particular, the flexible network deployment capitalizing on unplanned dynamic small cells (DSCs) is analyzed, and the associated slice-aware operation is highlighted. Under the light of evaluations, key design recommendations are provided. In addition, architectural enhancements are discussed along with the required signaling procedures to support such slice-aware DSC operation.**

Keywords—5G, Dynamic Radio Topology, Flexible Network Deployment, Network Slicing, Small Cells, Vehicular Nomadic Nodes

I. INTRODUCTION

The fifth generation (5G) mobile and wireless communications system is aiming at supporting a wide-range of services grouped under three generic service types, namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable and low-latency communications (URLLC). Besides, there can be services with requirements falling between the aforementioned service types, e.g., low-latency eMBB (LL-eMBB). Considering the diverse service requirements, the development of concepts for the 5G system (5GS) has progressed at a rapid pace. Within the 5GS, end-to-end (E2E) network slicing spanning over network domains (i.e., core network, CN, transport network, TN, and radio access network, RAN) where multiple logical networks corresponding to different business operations, aka vertical industries, are sharing one common infrastructure, is seen as a fundamental pillar [1]. 5G, powered by network virtualization and network slicing, shall thus give mobile network operators unique opportunities to offer new business models to consumers, enterprises, verticals, and third-party tenants and address such various requirements. To this end, both research projects [2]-[5] and standardization efforts [6][7] have described the main elements of the 5GS. Third generation partnership project (3GPP) has already completed the “non-standalone (NSA)” [8] and the “standalone (SA)” [9] releases of 5G by December 2017 and by June 2018, respectively.

The 5G services impose a diverse set of requirements that can change over time and space. Flexible network deployment via dynamic radio topology is an emerging enabler for the 5GS to cope with the spatially and temporally varying traffic conditions [10]-[14]. Compared to a fixed radio topology, dynamic radio topology comprising dynamic small cells (DSCs) offers on-demand activation and deactivation of the access nodes to respond to such variations in the network. Hence, dynamic radio topology decreases the total cost of ownership (TCO), where capital expenditure (CAPEX) is reduced, e.g., thanks to reduced need for deployment of additional *fixed* wireless access nodes, and operational expenditure (OPEX) is reduced, e.g., thanks to avoidance of site leasing, site search, and installation. One component to enable dynamic radio topology is the introduction of nomadic node (NN), aka vehicular NN (VNN), operation. An NN is a movable access node, i.e., a DSC, with a wireless backhaul link, which can be integrated into vehicles, e.g., within a car sharing fleet or taxi fleet. The availability of the NNs can vary over time and space, i.e., VNNs may change location and be available in another location. It is further assumed that an NN is only activated when the car is parked; thus, the NN is static during its operation.

In legacy networks, access nodes are deployed with fixed functional operation, e.g., decode-and-forward (DF) relay or amplify-and-forward (AF) relay, at pre-determined locations via network planning. In this work, the flexibility offered by network slicing in terms of protocol parametrization and the flexibility offered by dynamic radio topology in terms of spatial and temporal degrees of freedom are exploited to enable slice-aware DSC operation. Namely, the aforementioned design paradigms are analyzed jointly, where network slicing is extended toward 5G dynamic radio topologies. The latest 3GPP Release 15 specification is taken as the reference for the analyses, where disaggregated RAN architecture, i.e., central unit (CU) and distributed unit (DU) split is considered. It is shown that the functional operation of the DSCs shall be determined factoring in the topology variations as well as the slice requirements. In particular, topology variations can imply changes in the link qualities (e.g., wireless backhaul link due to co-channel interference) while slice requirements may require different latencies that can influence the tolerable protocol processing times at the NNs. Accordingly, the associated challenges are highlighted, and key design recommendations are given for the exemplified slices along with the signaling protocol needed.

The rest of the paper is organized as follows. Section II introduces the notion of dynamic radio topology and the associated differences to the conventional fixed radio topology. RAN support of network slicing is captured in Section III. Architectural implications are discussed in Section IV while evaluation results are provided in Section V. Conclusions are drawn in Section V.

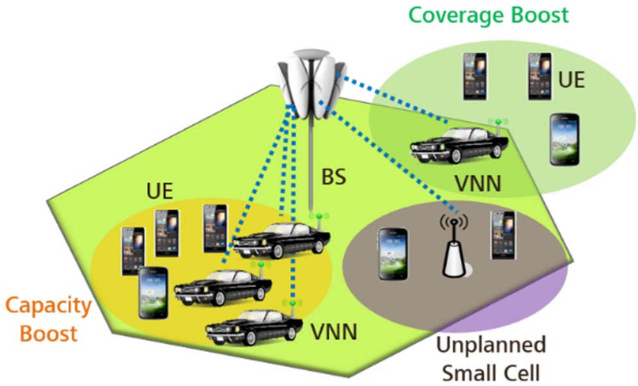

Figure 1 VNN operation and example benefits.

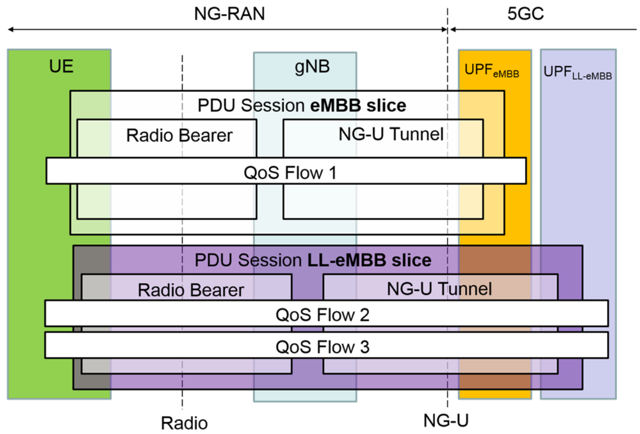

Figure 2 Slice support in the 5GS.

II. Flexible Network Deployment via Dynamic Small Cells

It is envisioned that 5G RAN will be much denser than the previous generations. One of the means of increasing the network density is the deployment of fixed small cells, for example picocells, femtocells, and relay nodes. Yet, one drawback of such fixed deployment, is that the full operation of all the nodes is *not* needed anytime and anywhere due to the notion of the inhomogeneous distribution of traffic over time and space. Hence, the fixed network deployment has the disadvantage of increased TCO. In addition, the need for searching a proper deployment site can further limit the achievable network topology.

On the other hand, NNs provide the envisioned temporal network densification within the framework of dynamic radio topology to tackle the inhomogeneously distributed service requirements appropriately. An NN is a movable access node that can enable demand-driven service provisioning to increase the network capacity and/or to extend the cell coverage area. NNs can be mounted on vehicles, e.g., within a car-sharing fleet, which are rapidly spreading over other cities globally [10]. Figure 1 depicts the NN operation along with several advantages. It is worth noting that the notion of a DSC can also be extended to unplanned small cell deployment, where the small cells can be activated/deactivated on a need basis, i.e., depending on the requirements of the target service and requested demand in a confined region. NNs are seen as a complementary enhancement to the existing infrastructure of a mobile network operator, which may already operate other types of small cells. The utilization of different types of the access nodes will be based on the needs and conditions of the operator taking into account the TCO of the deployment.

An NN may be associated with some uncertainty with regards to its availability, i.e., an NN may or may not be available in the target service region, for instance, caused by driver behavior. In addition, to attain the aforementioned benefits of NNs, a flexible backhaul shall be employed, where the capacity of the backhaul link can play a crucial role in the E2E user performance. The backhaul of an NN can be realized via a wireless connection, e.g., in-band half-duplex operation, out-band operation, and full-duplex operation. The NNs may be parked along a road or in a parking lot. That is, there can be more than one NN available in a region, among which one or more NNs can be activated as the serving NNs. In particular, NN activation and the corresponding process should be carried out in an autonomic manner without additional manual control in order to increase the operational efficiency, which is particularly important given that NNs may operate on vehicles' batteries.

III. Slice-Aware RAN Design

3GPP Release 15 specification for next generation-RAN (NG-RAN) comprises slicing awareness in RAN via network slice selection assistance information (NSSAI) including one or more single-NSSAIs (S-NSSAIs), which allow to uniquely identify a network slice [1][6][7]. While the fundamental slicing support is achieved by Release 15, e.g., granularity of slice awareness and network slice selection, various enhancements and optimisation can be considered for future releases. Such enhancements may imply, for example, specification-relevant signalling changes and implementation-dependent algorithms, e.g., related to resource management between slices.

In principle, network slicing offers additional degree of flexibility, where network functions (NFs) can be tailored according to the requirements of slice tenants. To this end, it can be expected that different tenants may have diverse network requirements. For instance, some slice tenants may only require a performance differentiation, e.g., in terms of Quality of Service (QoS) requirements, such as latency and data rate, which can be extended by further Service Level Agreement (SLA) requirements, such as number of connections for a given time and location.

Therefore, slice tenant requirements can be supported by different network slicing implementation variants [15]. In some of these variants, the whole RAN protocol stack can be shared by network slices where SLA differentiation can be performed with QoS enforcement. In particular, in line with the latest 5G Release 15 specification and as shown in Figure 2, for a network slice instance one or more Protocol Data Unit (PDU) sessions can be established, where a PDU session belongs to one and only one specific network slice instance [7]. Further, RAN maps packets belonging to different PDU sessions to different data radio bearers (DRBs), where within a PDU session there can be one or more QoS flows [6]. On this basis, the RAN treatment of different network slices can be in terms of radio resource management (RRM) schemes performed based on the QoS profiles of QoS flows mapped onto the respective data radio bearers (DRBs), where QoS profiles can include performance characteristics, e.g., packet delay budget (PDB) and packet error rate (PER), and allocation and retention priority (ARP).

From RAN perspective, the slicing requirements can be mapped onto:

- **Spectrum Requirements**: Slices may require different chunks of radio resources (e.g., below 6 GHz and mm-Wave radio) to meet the slice performance needs. In order to meet the spectrum requirements from multiple slices, slice-tailored resource management is required at RAN.
- **Functional Requirements**: Each slice may require different control plane/user plane functions and/or functional placements in order to provide optimized and agile performance at RAN. As stated in literature [5], network slices will allow for flexible functional placements and tailored network functions to meet the per-slice SLAs.
- **Isolation Requirements**: E2E slices shall be logically isolated. However, at RAN, the potential utilization of common infrastructure might provide a bottleneck towards complete isolation. In addition, given the slice criticality, each slice might have different requirement for isolation at RAN domain. Hence, the different isolation requirement per slice at the RAN domain might require sophisticated resource management to meet per-slice performance needs.

To meet the above requirements, inter-slice resource management, aka multi-slice resource management, is thus very important for improving the system efficiency, especially on shared infrastructure resources, which is a means for cross-slice optimisation. According to 3GPP, the inter-slice RRM can be supported by means of providing RRM split policies by the slice management system, as abstracted resource partitioning requirements for RAN [6]. RAN is responsible of enforcing these policies dynamically based on the actual channel conditions, bearer load and users' demand. The inter-slice resource management thus factors in the slice SLAs, e.g., to adapt the instantaneous radio resource allocation.

In addition to the slice-adaptive radio resource allocation, slice awareness can be extended to the so-called hard network resources, namely, wireless access nodes, particularly self-backhauled DSCs. That is, the slice support may not only include the conventional radio resources like time and frequency resources, but it can also include the adaptation of the network topology considering the DSCs available in a certain region. This is referred to as the *extended notion of a resource*. Accordingly, the slice-adaptive resource control shall also consider the changing radio topology including different access node types, e.g., micro-cells, pico-cells, relays, and NNs.

IV. Proposed Architectural Enhancements

One particular 5G deployment where the extended notion of resource can be applicable, is the CU-DU split of gNB, i.e., access node / base station (BS) in 5G, for allowing flexible centralization of RAN functions using adaptive topologies and functional placements [6][16]. In this context, slicing information can be exchanged between CU and DU, e.g., for radio bearer management in a slice-aware manner. Another possible deployment scenario is the integrated access backhaul (IAB), which makes use of the CU-DU split architecture and has been recently studied in 3GPP [17]. In IAB scenarios, IAB nodes can function as relays that can be connected to an IAB donor through a wireless backhaul link. The wireless backhaul link can employ below 6 GHz and above 6 GHz spectrum bands and can also support more than two hops (i.e., multi-hop operation). On this basis, an IAB node can include user equipment (UE) and DU functionalities, while the IAB donor can implement CU and DU functionalities. In this paper, the DSC is proposed to be interpreted as a wireless DU which can be separated from the CU (e.g., macro-cell site) for enhancing the per-slice key performance indicators (KPIs) in a slice-tailored manner. In this way, the F1 interface between CU and DUs, as specified by 3GPP, can be adopted for the wireless backhaul link [17].

For the fulfilment of network slice SLAs, the availability of wireless access nodes and the network topology shall be jointly considered along with the network slice requirements. This becomes particularly important when the network topology is changing as in case of self-backhauled DSCs, e.g., VNNs. The dynamic network topology can be exploited to better adapt to changing traffic conditions over time and space in cost-efficient way.

The wireless backhaul link of the DSCs can be reached by employing a relaying functionality. A fixed relay can be typically deployed as fixed radio frequency (RF) AF/repeater or layer 3 (L3) DF node [18]. As opposed to fixed functional operation in the literature, slice-awareness and 5G tight KPIs can necessitate on-demand flexible small cell operation. Slice-based target KPIs can comprise throughput / spectral efficiency (SE) for eMBB communications, high reliability and low latency for URLLC, and connection density for mMTC. Network slices may have different requirements in terms of throughput and latency, which necessitate enabling different operations for different types of traffic to meet certain KPIs. To this end, additional context can be utilized, such as the position of the DSCs at different parts of the cells and the associated channel link qualities. Furthermore, different functional operations of DSCs can have different E2E latencies (e.g., AF relaying imposes less latency compared to DF relaying thanks to fewer processing steps of the signals). On this basis, the appropriate relaying mode of DSCs can be determined, based on, e.g.,

- Slice requirements, such as latency and required data rate;
- Resultant performance of the utilized mode (e.g., throughput and latency);

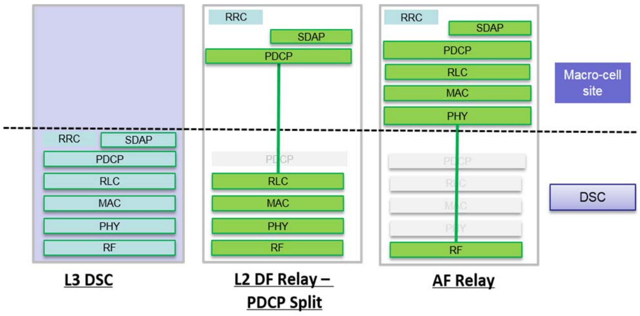

Figure 3 Illustration of various modes at DSC.

- Location of DSCs in the target service region (e.g., cell edge, cell middle, or cell center).

Different example functional splits among donor macro-site (i.e., CU) and DSCs (i.e., DUs) are depicted in Figure 3. Each functional split also implies a mode of the DSC. As mentioned above, different possible modes can be identified given the per-slice requirements, the backhaul channel (between macro and DSC) and the RAN conditions. In this context, the first option is the L3 DSC with full protocol stack, i.e., the L3 DSC can control the cell under its coverage, e.g., with a physical cell ID (PCI). In case of L2 DSC, a packet data convergence protocol (PDCP)-level split can be employed. The PDCP split could be more applicable in cases of frequent fast handovers (e.g. high mobility users) between the macro and DSCs, since PDCP re-transmissions would be required more often, and PDCP should be centralized for fast traffic forwarding. DF relaying option typically applies half-duplex operation to isolate backhaul and access links, and thanks to signal regeneration, there is no noise or interference amplification. Another option is the DSC to act as RF AF which functions as half duplex; however, AF mode may especially suffer from interference amplification, e.g., loop-back interference between backhaul and access links. These modes may not be confined to protocol stack layers, i.e., some of the functionalities at each protocol stack layer may also be split. For example, medium access control (MAC) functionality of hybrid automatic repeat request (HARQ) may be at the DSC, while another MAC functionality multiplexing/de-multiplexing may reside at the macro-cell BS. In this work, DF mode and AF mode correspond to L2 DSC and RF AF DSC, respectively.

The mode selection can be performed by a *dynamic RAN control unit* which can be located at the donor BS (e.g., CU) to which the wireless backhaul link connection is established. Such a control functionality can be considered as an extension to radio resource control (RRC) protocol layer. An example operation is depicted by a message sequence chart (MSC) in Figure 4. Therein, slice-aware mode selection is performed by the dynamic RAN control unit, where the needed slice information and QoS parameters can be obtained from the 5G core network (5GC), where DSC-related context information can be additionally utilized to decide on the appropriate DSC mode and the associated QoS parameters. The DSC mode thus can comprise radio bearer configurations. The necessary information elements are transmitted from the CU to the DSC in

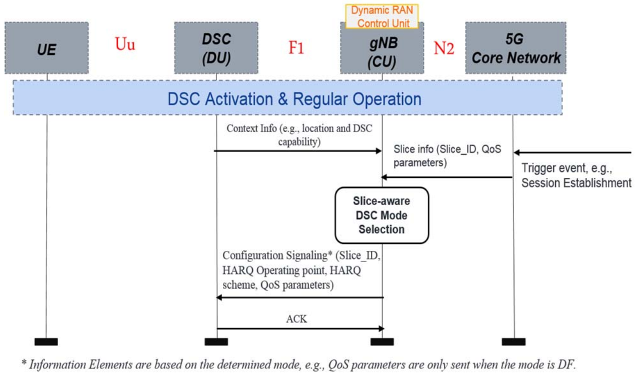

Figure 4 MSC for the operation of the slice-aware DSC mode selection and configuration.

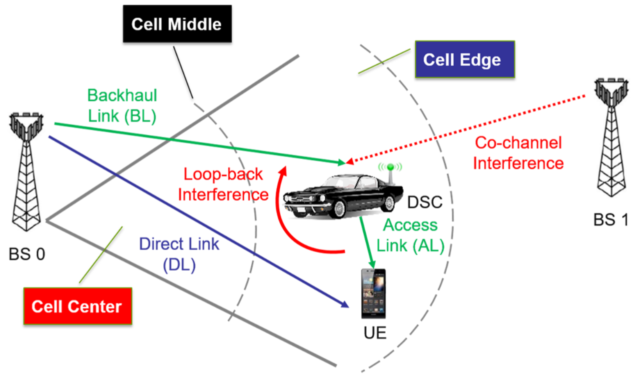

Figure 5 Example operation of the DSC with deployment locations. The interference sources for the AF mode is shown.

a configuration signaling message. The DSC can thereafter acknowledge the reception and application of the configuration.

V. Evaluations

The assumptions provided in [19] are taken as the basis for the relaying options, where a single DSC is considered either in the AF mode or the DF mode. Considering the links illustrated in Figure 5, the signal-to-noise-plus-interference ratio (SINR) on the E2E AF link at UE is given in terms of link signal-to-noise ratios (SNRs) on the individual links as

$$SINR_{\mathrm{AF}} = \frac{SNR_{\mathrm{BL}} \cdot SNR_{\mathrm{AL}} + SNR_{\mathrm{DL}}(1 + SNR_{\mathrm{TI}} + SNR_{\mathrm{BL}})}{SNR_{\mathrm{BL}} + (1 + SNR_{\mathrm{AL}})(1 + SNR_{\mathrm{TI}})}, \quad (1)$$

where BL, DL, and AL correspond to backhaul ink, direct link, and access link, respectively. TI marks the total amplified interference in case of the AF mode, which factors in the effect of loop-back interference and co-channel interference collectively. The SE of a link is calculated based on the Shannon approximation, i.e.,

$$SE_{\mathrm{link}} = A \cdot \log_2(1 + B \cdot SNR_{\mathrm{link}}), \quad (2)$$

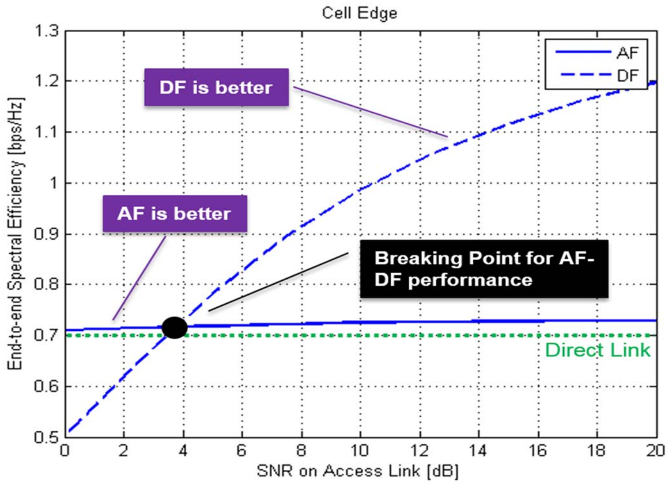

Figure 6 Example performance comparison between AF and DF modes. Breaking point shows the operation point where performances of AF and DF modes are the same.

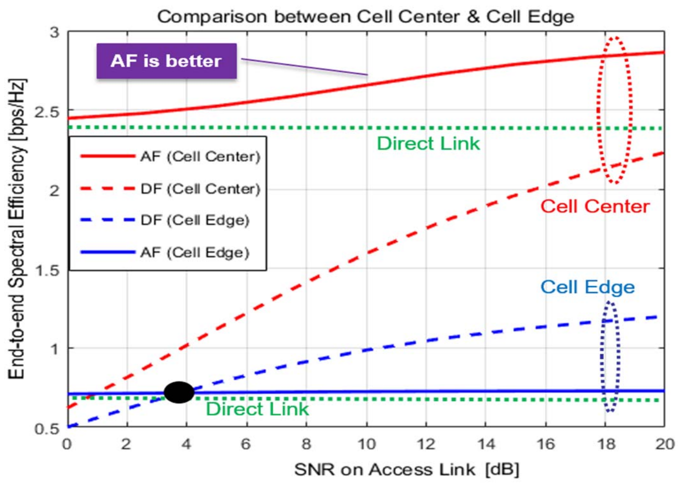

Figure 7 Example performance comparisons between AF and DF modes at the cell center and cell edge. AF performs better at the cell center while DF outperforms the AF on a wide range of operation points.

where A=0.88 and B=1/1.25 are the bandwidth and SNR efficiency factors, respectively. Assuming an optimal resource split between backhaul and access links in case of DF mode, the E2E SE of the DF mode is given as [20]

$$SE_{\mathrm{DF}} = \left(\frac{1}{SE_{\mathrm{BL}}} + \frac{1}{SE_{\mathrm{AL}}}\right)^{-1}, \tag{3}$$

where BL and AL correspond to backhaul link and access link, respectively.

In the MATLAB simulation set-up, the DSC is placed at the different locations inside the cell, i.e., cell edge, cell middle, or cell center as illustrated in Figure 5. During the operation, the DSC is static, e.g., while the vehicle is parked. Access link (between DSC and UE) SNR, i.e., SNR_{AL}, is varied from 0 dB to 20 dB. The SE of the direct link, i.e., SE_{DL}, is set as 0.7 bps/Hz at the cell edge, 1.2 bps/Hz at the cell middle, and 2.4 bps/Hz and the cell center. The backhaul link is assumed to be 5 dB better than the direct link, e.g., thanks to better antenna installations and lower noise figure [21]. Accordingly, given SE_{DL}, one can determine SNR_{DL} based on (2) and then SNR_{BL}, where SNR_{BL}=SNR_{DL}+5 dB. In order to account for the impact of amplified interference in case of the AF mode, the total interference levels (i.e., loop-back interference plus co-channel interference) are assumed as SNR_{TI}= [3, 2, 0] dB for cell-edge, cell-middle, and cell-center operations, respectively.

In Figure 6, an example case study is illustrated. In particular, the figure illustrates an example E2E SE performance (from BS to the UE via DSC, i.e., BS-DSC and DSC-UE link) of DF half-duplex mode and AF full-duplex mode versus the SNR on the access link. A direct link performance is also exemplified, where the direct link performance indicates the relative position of the UE with respect to the serving BS. In Figure 6, the performance breaking point between AF and DF modes is illustrated when the DSC is located closer to the cell edge. Due to the aforementioned impact of amplified interference, on most of the access link SNR values, DF mode outperforms the AF mode.

Besides, Figure 7 shows the performance comparisons considering both cell edge and cell center locations. It is shown that the DF mode outperforms the AF mode at the cell edge, where the interference is high and thus AF undergoes interference amplification. In the cell center, however, the AF mode outperforms the DF mode since the DF mode experiences performance loss due to the half-duplex operation [1].

In order to decide on the final DSC mode, the slice requirements shall also be taken into account. On this basis, in Figure 8, two network slices with different requirements on the SE and latency are depicted along with the performance comparison of AF and DF modes at the cell middle. It is to be noted that AF mode induces lower E2E latency compared to DF mode, because AF mode includes fewer amount of processing functions (i.e., only RF) and does not include a decoding of the signal (i.e., from RF up to RLC/PDCP). Additionally, the AF mode is typically full duplex, which implies no delay is introduced due to, e.g., half-duplex time-division multiplexing (TDM). When the UE access link SNR is 18 dB, as marked in Figure 8, the network slice 2 requirement on the SE can already be fulfilled by the AF mode. As the AF mode induces shorter latency, and network slice 2 has strict latency requirement, for network slice 2, the AF mode shall be configured. On the other hand, network slice 1 SE requirement can only be fulfilled by the DF mode and as the network slice 1 has relaxed latency requirement, for network slice 1, the DF mode shall be configured. Under the light of these analyses, it can be concluded that the performance of different modes, e.g., in terms of throughput performance, E2E latency, and reliability, shall be taken into account and based on the slice requirements, the DSC mode can accordingly be determined.

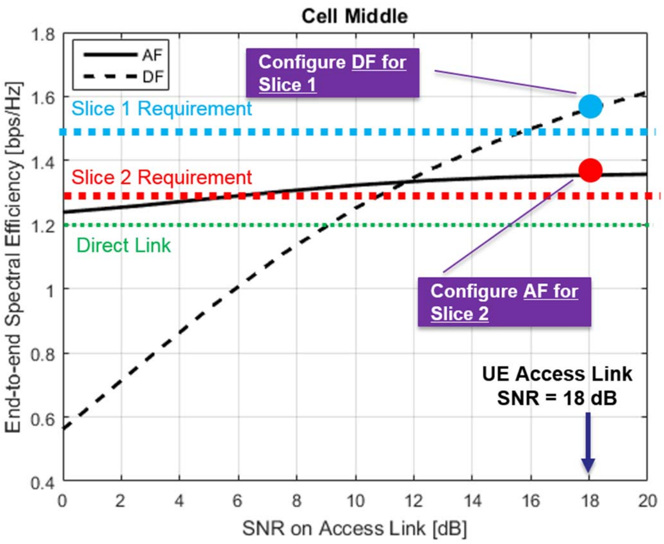

Figure 8 Slice-aware DSC mode selection which takes into account link qualities and slice requirements. Slice 1 requires 1.5 bps/Hz with *relaxed* latency requirement while Slice 2 requires 1.3 bps/Hz with *strict* latency requirement.

VI. CONCLUSIONS

This paper has presented the latest state-of-the-art in terms of network slicing and highlighted the emerging notion of dynamic small cells (DSCs). Network slicing provides network function level flexibility to support new business areas while DSC operation enables so-called flexible network deployment that can adapt to spatial and temporal traffic changes. On this basis, slice-aware DSC operation is proposed, and it is highlighted that a joint consideration of resultant performance of DSCs, e.g., depending on the location and link qualities of DSCs, and network slice requirements shall be taken into account in order to fulfill the tight slice key performance indicators (KPIs). Furthermore, the required architectural enhancements are outlined along with the protocol implications.

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