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Research Article

Waveform Flexibility for Network Slicing

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We discuss the idea of waveform flexibility and resource allocation in future wireless networks as a promising tool for network slicing implementation down to the lowest layers of the OSI (Open Systems Interconnection) models. In particular, we consider the possibility of cognitively adjusting the shape of the waveform to the requirements associated with various network slices. Moreover, such an adjustment of waveform shape is realised jointly with the selection and allocation of the appropriate frequency bands to each slice. In our approach, the definition of the waveform, as well as the assignment of resources, is done based on the information about the surrounding environment and each slice requirement stored in a dedicated context-information database. In this paper, we present the key concept of waveform flexibility for network slicing, the proposed algorithm for waveform selection and resource allocation among slices, and the achieved simulation results.

1. Introduction

It has been almost twenty years since the concept of cognitive radio (CR) technology was introduced for the first time as a method of effective usage of spectrum resources [1]. It was assumed that a cognitive terminal or cognitive system should sense the spectrum (or better, sense the ambient environment) to locate itself in the surrounding transmission context. However, the sensing feature, which should allow for accurate and stable identification of unused frequency bands or ongoing transmissions, if applied by the stand-alone device, is said to be not accurate enough to guarantee the required level of quality [2–4]. Thus, in consequence, the researchers and engineers started thinking how to bypass this problem in practical applications, and the implementation of the dedicated context-information database appeared to be a viable solution [5]. Such a database is populated with, possibly, up-to-date and precise information about the ambient context. The cognitive terminal or cognitive system will make a decision about spectrum occupancy and the best way of using the spectrum resources based on its sensing capabilities supported by the information stored in the database. In this situation, it is worth mentioning two regulatory approaches that utilise dedicated databases, which may act as some sort of confirmation that this approach can be considered for practical systems. First, European Telecommunications Standards Institute (ETSI) has focused their efforts on the Licensed Shared Access (LSA) scheme, devoted mainly for 2.3 GHz band, where the LSA repository and LSA controller support the functioning of the cognitive radio based system [6]. Second, in USA, the Federal Communications Commission (FCC) considered a solution called the Citizen Broadband Radio Service (CBRS). In this case, the dedicated Spectrum Access System (SAS) uses databases for managing of priority access users [7]. In a nutshell, databases are widely treated as one of the technical enablers for practical deployments of highly flexible, cognitive radio based systems.

On the other hand, recent developments in the domain of network management and in the general functioning of communication networks have shown great benefits of wide virtualisation of network functions. The definition of virtual network functions, as well as a network orchestrator, allows for a precise split and separation between the underlying hardware and the functions that have to be delivered. The successful application of this scheme in wired networks has resulted in a great interest among researchers in adopting this technique also to the wireless network, mainly to the radio access domain. It is, however, not an easy task in general due to the great variability of the typical wireless channel. Nevertheless, the successful investigation of network

virtualisation is strongly connected with another concept, called network slicing. Based on various definitions of what a network slice is [8, 9], one may understand a network slice as an autonomous virtual network, being a part (slice) of a bigger communication network, which is created to fulfil specific needs (and requirements) and which can be managed separately and solely by the slice owner (tenant). In other words, specific network functions will be selected and delivered, so that the tenant is able to communicate autonomously within the created virtual network, being now aware of the underlying devices and technologies. When it comes to the Radio Access Network (RAN), the slicing concept is often referred to as RAN slicing [10], and quite often the presence of virtual radio resources is considered there [11]. Moreover, when discussing wireless slicing, one may refer to slice scheduling, Physical Resource Block (PRB) scheduling and traffic shaping [8] and, in general, inter-slice resource scheduling [12]. Interesting approach for inter-slice resource sharing based on graph colouring has been presented in [13], where the slices have been allocated in the Time Division Duplex (TDD) networks. The solutions proposed there assume that entire spectrum is allocated to the slice, and the traffic conditions are reflected in proper definition of uplink/downlink ratios. In [14] the authors proposed the application of so-called Network Slice Broker, the entity enabling mobile virtual operators to request resources in dynamic way via proper signalling.

Bearing the two above observations in mind, one may say that both cognitive radio and network/RAN slicing with network function virtualisation offer much flexibility to the network designers. However, as network slicing is more of an overall view of the communication network, cognitive radio is more focused on lower layers, mainly on the physical and medium access layers, and as such is more connected to RAN slicing. In fact, we claim that the functionality delivered by the cognitive radio technology can be treated as technical enabler for the practical deployment of the network/RAN slicing concept. In particular, we claim that the ability to dynamically adjust the waveform, as well as to adaptively assign the frequency band, is crucial for future implementation of the slicing concept. Following the idea of virtual resource blocks, one may imagine that the requirements for each slice may be specified in a generic way, meaning only the technology-independent constraints could be identified. For example, one may define a slice by defining the requirements on rate and latency, which may be translated into a specific set of virtual resource blocks, which in turn have to be mapped to specific (real) spectrum resources. In such a case, the cognitive radio technology can play its role by allowing a dynamic definition of the best waveform for data transmission, as well as by the proper association of the frequency band with the slice. In this paper we concentrate on the last functionality, and mainly we discuss the algorithms for adaptive selection of the waveform and the solutions for adaptive allocation of frequency blocks to the slices subject to fulfilment of their requirements on rate and Signal to Interference plus Noise Ratio (SINR). The algorithms are defined from the point of view of resource provider, i.e., the entity that delivers spectrum resources to various tenants who use slices for the delivery of their services. The spectrum provider wants to allocate appropriate frequency resources to specific slices in a way that maximises its revenue from spectrum licensing. It is also worth mentioning that the concept of waveform flexibility was first introduced in [15], where the primary system operating in the TV band was protected by the appropriate selection of the best waveform. This idea is extended in this work by adding the solutions for dynamic frequency allocation to the slice. Thus, the novelty of the paper is twofold; first, it extends the concept of waveform flexibility to network/RAN slicing, and, second, it proposes the algorithm for joint waveform and frequency band allocation among slices. The novelty of this manuscript can be summarised in the following way:

(i) First, we define the new concept of waveform adaptation and selection as part of the first, we define the new concept of waveform adaptation and selection as part of the network slice creation process, which is assumed to be fully dynamic and which maximises the resource provider revenue; we extend the work of [15], where the general idea of the waveform selection was initially discussed;

(ii) Second, we propose a joint scheme for waveform selection and resource allocation, and then we propose a two-step algorithm for network slice creation by spectrum and infrastructure provider;

(iii) Third, we have tested three algorithms for resource allocation that minimise the newly defined fragmentation coefficient.

The paper, being a sort of position paper, is organised as follows. First, we provide the scenario definition explaining the role of (a) spectrum and infrastructure provider (SIP) who offers its resources to (b) service provider (SP). Next, we present the network slice definition from the point of view of the lowest layers of the OSI stack model, which we applied in our research. In the following sections, we discuss the waveform selection idea and the frequency allocation problem, and we provide the proposals of three heuristic algorithms trying to solve these problems. The simulation results for four separate use cases are presented afterwards, and the entire work is summarised and concluded in the last section.

2. Problem Definition

In our work we consider the presence of a spectrum and infrastructure provider, whose assets include both infrastructure and spectrum resources with active licenses. The provider is interested in efficient usage of their available resources by dynamic creation of network slices for various types of end-to-end data transmissions. Moreover, their ultimate goal is to maximise the total revenue through maximising instantaneous spectrum usage and minimisation of various costs (in our case, it is the cost of consumed energy).

There is also a set of N prospective network operators (stakeholders, tenants) willing to deliver new services to end

users, but they do not want to invest in infrastructure and apply to the regulator for long-term licenses. Thus, these tenants would like to use the resources of the SIP by utilising the benefits originated by the network slice technology. These tenants are referred to as service providers to the end users.

In general, various slices may be created following the specific requirements defined by the interested stakeholders. One may refer to the recent work within 3GPP [16], where the network slicing is discussed as a vital part of the system architecture for the 5G systems. The functional description identifies the so-called Network Slice Selection Function (NSSF). The authors of [16] also inform that the network slice is defined within a Public Land Mobile Network (PLMN), and it should include the core network control plane and user plane network functions. Furthermore, within the serving PLMN, it should include at least either the new Next Generation Radio Access Network (NG-RAN) or the Non-3GPP Interworking Function (N3IWF) to the non-3GPP access network. It is claimed that network slices may differ for supported features and network functions optimisations and that the operator can deploy multiple network slice instances delivering exactly the same features but for different groups of end users. In that context, the so-called Network Slice Selection Assistance Information (NSSAI), which identified the network slice, consists of two fields: SST, standing for Slice/Service Type, defining the expected slice behaviour, and SD, Slice Differentiator, to distinguish among multiple network slices of the same SST. The standard [16] specifies three SSTs, mainly:

(i) for SST set to 1, the slice for 5G enhanced Mobile BroadBand (eMBB) type of traffic is considered;

(ii) for SST set to 2, the slice for handling Ultra Reliable Low Latency Communications (URLLC) is envisaged,

(iii) and finally, for SST set to 3, the slice for massive IOT (mIOT) type of traffic is proposed.

However, the standard does not specify the strict values of the features that have to be guaranteed by a specific slice, and this issue is still left open for implementation. The strict performance requirements for various scenarios (e.g., for high data rate and traffic density scenarios, for low latency and high reliability, and high accuracy positioning) are specified in [17].

Similar approach is presented by GSM Association in [18], where various exemplary slice requirements have been presented. One may identify the following suggestions (we present here only a subset of long list of various prospective applications):

(i) for augmented and virtual reality applications, the network slice shall consider various aspects of video codecs; for example, for strong interactive virtual reality schemes it is envisaged that the expected needed data rate could vary from 120 Mbps to 3.36 Gbps, the Round-Trip-Time (RTT) shall vary between 5 and 10 ms, and the acceptable packet loss is not greater than 10^{-6}. However, these values differ significantly if one looks at the requirements for weak-interactive virtual reality schemes, where the required data rate varies between 40 Mbps till 2.34 Gbps, and the allowable RTT is between 10 to 30 ms.

(ii) For automotive applications, there are not strict values provided, one may find the generic statement that mobile system shall provide ultra reliable and low latency communications between vehicles.

(iii) For the energy applications the requested bandwidth shall be around 1 kbps per user, the end-to-end latency shall be below 5 ms, the packet loss is less than 10^{-9}, and the availability is above "five nines".

(iv) For healthcare application, the definition of the important requirements is left for further investigation.

Thus, one may observe that there are no strict requirements associated with a generic slice of eMBB, mIOT, or URLLC traffic types in [18]. Similarly, in [19] the requirements put on various slices are defined in a highly generic way for the three fundamental traffic types, eMBB, URLC, and massive machine type communication, mMTC. Let us stress that the presented work concentrates on the ways for allocation of the physical resources certain slices (in particular, how the waveform can be selected and how the spectrum resources will be assigned), which is not a subject of standardization yet. One may observe that when the number of waveforms is fixed, the selection of the best one for given slice may be done in the analogous way as it is done nowadays for, e.g., selection of modulation and coding schemes.

As, theoretically, the number of various slices managed within one network is not limited, in order to make the analysis more tractable, we limit the number of different tenant types (which corresponds to different slice definitions) to three, mainly mIOT, eMBB, and URLLC types, as specified in [16]. The former one will be characterised by moderate latency and relatively low throughput, whereas the latter, by high requirements on the achieved rate. Let us stress, however, that the limitation on the number of slice types does not entail any requirements on the number of tenants of each type. It means that the SIP may create a few network slices of both types.

In the context of OSI layers, there is still debate as to how the network slices should be incorporated into the lowest layers (mainly physical and medium access control). From this point of view, we assume that the slice itself will correspond to the set of requirements that have to be guaranteed by the created virtual network, and the fulfilment of these requirements may be achieved by adaptive definition of various parameters. In particular, we consider that the SIP (i.e., the entity responsible in our case for network slice creation) will be able to adapt the waveform shape to the slice definition and to instantaneous channel conditions. Moreover, a dedicated algorithm for spectrum band assignment to the slice will be run on the network part in order to maximise the revenue of the spectrum provider under the constraint of permanent fulfilment of slice-specific requirements. In our analysis, we assume that

the network slice will be created at least in a minute scale; i.e., the assignment of frequency bands to the slices is not a problem of classical resource scheduling applied to cellular networks (like proportional fair or round-robin), but more of creating an appropriate frequency allocation plan among base stations. Moreover, once the frequency band is associated with a certain slice, the dedicated scheduler may run within that slice to allocate resource blocks among the slice users. It also means that the SIP will try *to pack* various tenants in such a way that the spectrum utilisation is maximised, and such spectrum assignment is valid for a relatively longer time.

3. Slice Definition

As mentioned above, without the loss of generality, we have limited our analysis to three most common types of slices: a low rate slice for mIOT type of traffic, a high rate one for eMBB service providers, and one called URLLC for low latency schemes. From the perspective of lower layers of the OSI model, the slice will be characterised by a set of parameters describing the requirements that must be guaranteed by the SIP to the tenants. Following the discussion in previous section, as well as the observation presented in [16–19], we agree that there is not one strict definition of the set of requirements for a certain network slice. Assuming the application of network virtualisation and cognitive ratio terminals, it will be the role of the SIP to map the requirements onto the available physical resources (e.g., spectrum bands) so that the assumed quality of service requirements within the network slice is satisfied. Having this in mind, the mIOT slice may be in general defined as a network where the rate of some tens or hundreds of kilobits per second per one user is acceptable, and there are no strict requirements on data delay; i.e., delays typical for cellular networks are acceptable. It is also expected that simple and mature technologies may only be applied, as the cost per one chip, as well as the overall energy consumption, should be minimised. The possible physical layer technologies fulfilling these requirements are, for example, the traditional GSM transmission scheme, or such solutions as Long RAnge (known as LoRA), SigFox, Long-Term Evolution for Machines (LTE-M), or Narrowband Internet of Things (NB-IOT) [20]. For our further analysis we assume that the Gaussian Minimum Shift Keying (GMSK) transmission occupying 200 kHz will be applied. We also assume that the number of active channels may vary in time.

Analogously, the eMBB network will require the rate of a few megabytes or more per one user, and there are again no rigorous requirements on the network slice latency. The end-user devices are expected to have relatively high processing power, so more advanced technologies such as Long-Term Evolution (LTE), LTE-Advanced (LTE-A), or New Radio (NR) may be considered. However, the energy consumption should always be kept at the lowest possible level. Similarly, the URLLC network may be characterised by extremely strict requirements on latency and reliability and relatively high requirements for the traffic rate.

4. Waveform Selection Idea and Frequency Allocation Problem

As stated above, the key research problem is to find the way for spectrum usage maximisation (and, in turn, revenue maximisation due to spectrum leasing) by, first, adaptive selection of the waveform shape within the slice and, second, through smart allocation of frequency band to each slice. It can be easily observed that the selection of the waveform immediately entails the occupancy of certain spectrum by the slice, and thus it has a potential impact on the frequency allocation algorithm. At the same time, each waveform can be characterised by its computational complexity (or more precisely, the number of required mathematical operations per one transmitted bit), as defined in [21]. Thus, more advanced waveforms (such as noncontiguous, filtered multicarrier schemes) may guarantee narrower spectrum at the expense of advanced and computationally intensive processing. Narrower spectrum associated with given waveform (thus, with slice as well) may cause more slices of the same type to be created within a certain frequency band W. But on the other hand, a service provider (i.e., the entity for whom the slice is being created) may be interested in as simplified processing as possibl and will accept advanced waveforms only in specific situations or at a higher price. Moreover, more advanced waveform needs typically more sophisticated processing and power consumption; thus it may have slight but negative impact on the overall end-to-end delay of the link. In consequence, assuming that there are N various waveforms to select from, one may calculate the corresponding transmittance of each waveform $H_n(f)$ for n=1,2...N, and one may compute the number of necessary mathematical operations (see [21]), denoted as β_n, and the associated processing power $P_n^{(\beta)}$. In such a case, one may think about the joint optimisation algorithm that would find the best solution; i.e., it will maximise the SIP's revenue ψ by the proper selection of the waveform and frequency band. Various factors can be considered in the definition of the revenue, such as requested bandwidth $B_s \leq W$, network slice lifetime T_s (i.e., the requested time for which the slice has to be maintained), requested coverage area A_s, and expected end-to-end delay θ_s. In that context, the highly generic formula for the revenue could be defined as function of the abovementioned factors, i.e., $\psi(B_s, T_s, A_s, \theta_s, P_n^{(\beta)})$. Clearly, the more resources (e.g., bandwidth, allocated time, covered area) are requested, the greater revenue shall be expected. At the same time, the more advanced waveform is selected, the more processing power and costs at the SIP side is envisaged. Depending on the exact definition of the revenue function, appropriate waveform selection and resource allocation algorithm will be selected. In our approach, we assume the following:

(i) first, there are no priorities between service providers,

(ii) second, the SIP acts in a greedy fashion; i.e., there is a willingness to serve each incoming request from service provider, and only the lack of resources prevents the SIP from creation of a new slice

(iii) third, the considered revenue of the SIP increases with the requested rate, and decreases with the processing cost

(iv) finally, the SIP processes the incoming requests immediately at the time they appear in the system, and there is no queue for nonserved SPs.

In consequence, the SIP is interested in delivering services at the lowest cost (based on the third assumption), so it will try to select the simplest, yet spectrally efficient, waveforms minimising the processing costs. Please note, also, that the SP is also interested in utilisation of the simplest waveforms, as the selection of advanced solutions by the SIP entails more severe processing also at the SP devices. Thus, we have decided to split this problem into two subproblems, knowing that the optimal solutions cannot be achieved, but such an approach makes the problem practically tractable. In the first step, we check the possible set of waveforms that could theoretically be assigned to the new slice, and from this set we select the one that guarantees the simplest processing (i.e., it achieves the lowest energy consumption due to the lowest number of required operations per one transmitted bit). Once the waveform is selected, we try to find the best allocation of the considered slice in the frequency domain. We assume that the entire considered frequency band of bandwidth W is split into C equal channels, each of bandwidth W/C. Adjacent unused channels (vacant channels) create channel blocks, which are interwoven with the channels already allocated for network slicing. If there are $C(i)$ adjacent vacant channels in block i, the total bandwidth of the channel block i is equal to $C(i)W/C$. For example, let us assume that the band of 20 MHz is split into 40 channels each of 500 kHz bandwidth. Originally, when no slice is created and all channels are unused, there is one block of 40 channels. When two channels in the middle (e.g., the 19th and 20th channel) are assigned to a particular network slice, there are two channel blocks that can be further allocated to new network slices. The first block consists of 18 channels, and the second block consists of 20 channels. These two blocks in the frequency domain are interwoven with a 2-channel-wide spectrum block.

In the following, we describe these two phases in more detail. Let us also mention that in our analysis we initially assume that the service providers (tenants) are interested in delivering their services over possibly wide areas with the highest possible signal quality. Thus, we assume a fixed and constant value of the transmit power in each slice. However, it is worth mentioning that the potential introduction of power adaptation creates further degrees of freedom in system design but is intentionally left for further study.

4.1. Step I: Waveform Adaptation. Following the assumption mentioned in the previous sections, the goal of this phase is to find the simplest waveform, which will allow for achievement of the requirements defined in the request delivered by the SP. It can be mathematically represented as follows:

$$\min \quad \sum_{n=1}^{N} \varepsilon_n P_n^{(\beta)}, \tag{1a}$$

$$\text{s.t.} \quad R \geq R_{\text{req}}, \tag{1b}$$

$$T \geq T_{\text{req}}, \tag{1c}$$

$$A \geq A_{\text{req}}, \tag{1d}$$

$$\varepsilon_n \in \{0, 1\}, \tag{1e}$$

$$\sum_{n=1}^{N} \varepsilon_n = 1, \tag{1f}$$

$$\bigwedge_{m \in M} \sum_{n=1}^{N} \varepsilon_n P_{l,m}^{(n)} \leq \breve{P}_{I,m}, \tag{1g}$$

where R_{req}, T_{req}, and A_{req} represent the requirements on rate, time, and area specified by the SP in its request for network slice creation and R, T, and A are the assigned resource corresponding to rate, time, and area. ε_n is a Boolean variable for nth waveform. Moreover, assuming that there are already M created network slices, $P_{l,m}^{(n)}$ defines the total interference power induced into the other already served system m when the n-th waveform is selected, and the value of the interference power cannot exceed the maximum acceptable interference for that system denoted as $\breve{P}_{I,i}$. This aspect is discussed in detail in the following sections.

The initial concept of dynamic waveform definition was originally discussed in [15]. It was observed there that contemporary wireless communication systems utilise various adaptation procedures in order to improve the performance of wireless data delivery. Various transmit parameters may be adjusted in the wireless communications systems today, such as the selection of various modulation and coding schemes (MCS) or adjustment of transmit power via open or closed power control loops. In [15] we proposed to consider waveform flexibility, where the cognitive terminal may decide to select one of four available waveforms for data transmission, mainly, traditional Orthogonal Frequency Division Multiplexing (OFDM) signalling or Filter Bank-Based Multicarrier (FBMC) schemes [22] and their non-contiguous versions, NC-OFDM, and NC-FBMC [23]. The ultimate goal in that work was to use vacant spectrum while protecting the primary transmission, mainly the Digital Video Broadcasting–Terrestrial (DVB-T) signal.

In this work, we focus on horizontal sharing scheme, where the set of frequency resources (licensed to one party, a SIP in our case) will be shared among all interested stakeholders (the SPs) and no priorities are considered between them. The dynamic mechanisms are considered here as support for slice creation at the physical and medium access layers, and these slices are assumed to be of identical importance. It means that all existing transmissions have to be protected, and the new network slice will be created only in a case, when no harmful interference will be induced into any of the already existing slices. Moreover, limited set of available waveform are taken into account, and mainly we have selected the Gaussian Minimum Shift Keying (GMSK) scheme as suitable for the mIOT slice and contiguous and noncontiguous multicarrier signals (OFDM and NC-OFDM) for the eMBB one. The noncontiguous multicarrier scheme

has the advantage that it can efficiently utilise even highly fragmented spectrum, which is interweaved with other transmissions. The main cost of such approach is the increased number of operations to be performed per one second and increased control information overhead, when compared to the classical OFDM scheme. Let us remember that the ultimate goal of the spectrum and infrastructure providers is to maximise their revenue, while minimising any unnecessary costs. Thus, we claim that depending on the situation (i.e., how much interference can be induced to neighbouring systems) the transmitter should select the simplest possible waveform shape that guarantees the achievement of the defined requirements. Thus, it should first prefer to select the contiguous transmission scheme (i.e., OFDM), and if the selection of the contiguous band is not be possible, the noncontiguous versions of this multicarrier scheme can be applied. Such an approach is justified, as the overall complexity of the OFDM case is much lower than that of NC-OFDM.

Assuming that the tenant is capable of using all waveforms, the following algorithm for waveform selection phase will be applied:

(i) for given requirements (e.g., on average rate), check the possibilities of application of the simplest waveform (in our case GMSK); if it is possible, go to phase 2 of the algorithm and try to assign frequency resources for GMSK-based slice; if this is possible, the algorithm is finished and slice is created;

(ii) if the achievement of assumed technical requirements is not possible with GMSK or it is not possible to assign frequency resources, check if it is possible to apply OFDM signalling and, if yes, try to assign frequency bands for OFDM slice;

(iii) when the achievement of assumed requirements is still not possible, follow the same procedure with NC-OFDM scheme.

4.1.1. Interference Analysis. The assignment of specific frequency bands to the slice is strongly connected with the need to keep the mutual (also aggregated) interference below acceptable level. In our scenario we assume the same hierarchy of all slices, thus the problem of mutual interference has to be considered within each pair of coexisting slices (systems). Let us recap that the interference observed between neighbouring frequency channels is caused by the imperfections of the real transmitter (such as the characteristics of the impulse shaping filter and nonlinearities at the radio front end leading to Out-Of-Band Emission, OOBE) and receiver (e.g., non-ideal selectivity of the reception filters). The problem at the transmitter side is addressed by providing (typically provided precisely in the standards) a definition of the spectrum emission mask (SEM), which specifies the requirements on the minimum transmitted signal attenuation at a given frequency. At the same time, the design of the reception filters at the receiver side (thus, its transmittance) is typically left to manufacturers. Although the minimum selectivity level can be specified in standards as well, its characteristics (averaged over various designs) can be retrieved by measurements. These two sources of imperfections illustrate two sources of interference observed between adjacent (in the frequency domain) wireless systems. In particular, SEM specifies how much power may be introduced to the neighbouring channels if the transmitter sends a signal with a given power. Analogously, the frequency response of the effective reception filters defines the amount of unwanted power intercepted by the receiver from the neighbouring bands. In the literature, these two phenomena are described mathematically by

(i) Adjacent Channel Leakage Ratio, ACLR, which describes the ratio between the power transmitted in the nominal band of the system and the power observed in the adjacent band

(ii) Adjacent Channel Selectivity, ACS, which informs about the ratio of receiver filter attenuation on the band of interest and filter attenuation on the adjacent channel frequency.

Typically these two factors are often represented jointly as the Adjacent Channel Interference Ratio, ACIR, defined in linear scale as

$$\frac{1}{ACIR} = \frac{1}{ACLR} + \frac{1}{ACS}. \tag{2}$$

To be more specific, the total interference power introduced to a given system can be calculated in the frequency domain as

$$P_I = \int_{-\infty}^{\infty} PSD(f) \left|H^{TR-RX}(f)\right|^2 \left|G^{RX}(f)\right|^2 df, \tag{3}$$

where $PSD(f)$ is the power spectral density at the output of the interfering transmitter antenna (including the power allocated to given symbols/subcarriers, symbol shaping in digital domain, digital-analogue converter characteristic, and frequency response of the transmit—TX—antenna), $H^{TR-RX}(f)$ is the channel frequency response (considering channel attenuation and multipath propagation effects), and $G^{RX}(f)$ is the frequency response of an effective receiver filter (including the reception—RX—antenna characteristics, analogue frontend characteristics, and demodulator characteristics). The formula (3) provides precise method of interference calculation. However, in many cases it is not practical as the current channel fading is unknown. From this perspective it is not needed to limit instantaneous interference power, but it is enough to constrain expected interference power, i.e., E[PI] assuming the only random variable is channel coefficient under fast fading. Therefore,

$$\begin{aligned} E[P_I] &= \int_{-\infty}^{\infty} PSD(f)\, E\left[\left|H^{TR-RX}(f)\right|^2\right] \left|G^{RX}(f)\right|^2 df \\ &= \alpha \int_{-\infty}^{\infty} PSD(f) \left|G^{RX}(f)\right|^2 df \end{aligned} \tag{4}$$

assuming that mean channel coefficient power $E[|H^{TR-RX}(f)|^2] = \alpha$ is constant over some period and

independent of f. This is true, e.g., for Rayleigh fading. It can be argued that for sufficiently rich multipath propagation environment and sufficiently wide considered bandwidth the channel attenuation at some frequency will be connected with channel amplification at some other frequency making the expectation close to real instantaneous interference power. We do not claim that the wireless channel is flat although locally, at a given frequency f, it can be treated as flat (e.g., this is a reason for vast usage of OFDM modulation nowadays). As such, the wireless channel can be characterised by a single coefficient α being reversely proportional to the channel path loss giving

$$P_I = \alpha \int_{-\infty}^{\infty} PSD(f) \left|G^{RX}(f)\right|^2 df. \quad (5)$$

Defining the total power transmitted from the interference source as

$$P_{TX} = \int_{-\infty}^{\infty} PSD(f)\, df \quad (6)$$

ACIR, being the ratio of interference power at the antenna of the victim receiver to the effective interference deteriorating its performance, is defined as

$$ACIR = \frac{\alpha P_{TX}}{P_I}. \quad (7)$$

This definition is very useful in calculating the effective interference power between slices as

$$P_I = \frac{\alpha P_{TX}}{ACIR}, \quad (8)$$

where ACIR measures the interference coupling between the transmitter and receiver, independent of the transmission conditions, and transmission power. The assumption about ACIR independence from TX power is typically used, although it can be incorrect if nonlinear effects take place in the transmitter or receiver; e.g., frontend saturation in the interfered device is possible if the interfering system is located in a relatively near distance and is transmitted with relatively high power. There are various ways of obtaining transmitter/receiver frequency characteristics:

(i) Based on measurements: In this case all characteristics of transmitter/receiver are assessed during all processing phases (both analogue and digital). However, the obtained characteristics are specific for a given transmitter/receiver pair and the signal configurations used during measurements.

(ii) Based on standards: In this case, the worst case interference generation/rejection is specified. Although any produced device has to obey the specified limits, it will result in the lowest possible ACIR between systems.

(iii) Based on transmitter/receiver modelling: It requires knowledge about the modulation/demodulation used. Although ACIR in many scenarios can be calculated accurately, it requires some assumptions about the analogue frontend.

In our analysis, we consider the presence of two classes of slices. The first one utilises GMSK modulation (it is the class consisting the mIOT traffic; thus mIOT slice is part of it), whereas the second allows for the adaptive adjustment of the multicarrier signal by using either OFDM or its noncontiguous version (it is the class tailored for eMBB and URLLC traffic). The considered slicing model assumes all OFDM-based slices are orthogonal to each other (in order to reduce mutual interference to zero). It can be simply obtained if the transmitter spans the whole available bandwidth providing independent subcarriers to each OFDM-based slice. However, the mutual interference between GMSK and OFDM has to be considered. The GSM transmitter and receiver characteristic are based on standard-based receiver rejection characteristics in [24] and standard-based transmitter characteristics [25]. The calculation method is based on the method presented in [23]. The GSM-GSM ACIR calculation is based on the abovementioned transmitter/receiver characteristics with the calculation carried according to (5).

4.2. Step 2: Frequency Allocation. In the first step of the procedure, we select the best waveform, taking into account the requirements defined in the slice, in particular, the limitations regarding the available waveform shape and the constraints on the consumed energy. Once the prospective waveform is defined, the crucial point is to select the appropriate frequency band, such that the instantaneous spectrum fragmentation is minimised. We claim that it is easier to allocate a new network slice in the physical layer (mainly by assigning spectrum resources to the spectrum slice) if the spectrum is not fragmented; i.e., the vacant channels are wide and are not interwoven with ongoing transmissions. In that sense, the worst case is when the set of occupied channels and vacant channels creates a comb-like form in frequency domain. In such a case, only very narrowband channels are available; thus either slice that requires narrow bands can be allocated, or sophisticated noncontiguous multicarrier schemes have to be applied (i.e., where many narrow gaps in the spectrum are used for data transmission).

In order to provide the maximum flexibility to the SIP, it should have the ability to allocate spectrum to various slices with possibly minimum computational load. One may observe that the more fragmented spectrums (i.e., the more narrowband gaps of unused spectrum in the considered band), the less degrees of freedom in allocation of resource do the new slice. Spectrum fragmentation may result in a situation, when some SP (which are not capable in usage of advanced waveforms, such as noncontiguous schemes) will be not served by SIP, although theoretically SIP will have enough resources for such a new slice. Thus, the frequency allocation process should prefer such allocation schemes that will minimise the spectrum fragmentation or, in our approach, maximise the fragmentation coefficients. In our experiment, we have defined the fragmentation coefficient μ as follows:

$$\mu = \frac{\sum_{i=1}^{S} C(i)^2}{C^2}, \quad (9)$$

where S is the number of unused spectrum blocks, $C(i)$ defines the number of channels within the i-th block (i=1,. . ., S) of vacant channels, and C represents the total number of channels in the considered spectrum range W. This coefficient equals 0 when the whole spectrum is occupied and 1, when no channel is used. In order to increase the importance of wider bands, the number of channels within each block is squared. For example, if there are two 3 MHz wide blocks of unused channels, it is a worse case when compared to the situation when the blocks are of the width of 1 MHz and 5 MHz, respectively. Please note that, without the power coefficient set to 2, these two exemplary cases will have the same value of the μ coefficient. Furthermore, please observe that the assumption that the SIP wants to maximise the spectral efficiency guarantees that the algorithm will not try to keep the fragmentation coefficient close to zero by not allocating the spectrum to anyone. In other words, each new request for slice creation has to be realised only if there is a space in the frequency domain.

Having in mind the definition of the fragmentation coefficient and knowing that the n-th waveform is chosen, the optimisation goal can be defined as

$$\max \quad \mu, \tag{10a}$$

$$\text{s.t.} \quad R \geq R_{\text{req}}, \tag{10b}$$

$$T \geq T_{\text{req}}, \tag{10c}$$

$$A \geq A_{\text{req}}, \tag{10d}$$

$$\bigwedge_{m \in M} P_{l,m}^{(n)} \leq \check{P}_{I,m}. \tag{10e}$$

We have proposed and tested three separate pragmatic algorithms for frequency assignment to network slices, and the three are discussed in detail below:

(i) *Method A* (also marked later as *linear*): in this approach, the new slice is allocated at the first possible position in the spectrum starting from the lower bound of the available frequency band; in other words, once the waveform is selected, the algorithm searches for the first available position, taking into account the requirements on ACIR and SIR. To put it simply, the algorithm will assign the first available channel (or channels) from the left side of the available spectrum band, for which the requirements are fulfilled.

(ii) *Method B* (also marked later as *sinr*) also allocates the spectrum starting from the lower bound of the available frequency range, but it modifies method A in such a way that it maximises the value of final SIR in the system (i.e., observed after frequency allocation). As SIR will increase as the distance between the signal spectra in the frequency domain also increases, the following behaviour of the algorithm is expected. In particular, in the first step, the algorithm will allocate to the slice the frequency band on the first available channels and, in the second step, the new network slice will be allocated mostly as far as possible (in spectrum domain) from the existing transmission (therefore, on the right bound of the available frequency band). If the third slice is created, it will be allocated in the middle of two existing transmissions in the frequency domain.

(iii) *Method C* (also marked later as *fragmn*): as the two previous methods allocate the spectrum based on SIR criteria, the third method follows the brute-force search strategy with regard to the fragmentation coefficient μ. In other words, it searches for the best allocation of frequency resources which maximise the fragmentation coefficient μ.

Please note that in general SINR value should be considered here. However, one may observe that the proposed methods will be applied within one base station, and in consequence the impact of noise and path loss observed in each location of the covered area will be the practically the same for each slice (i.e., for given location the path loss and noise will be the same for each slice, if these slices are created within the same base station). Knowing that 1/SINR=1/SNR+1/SIR, we may remove the SNR component in the frequency allocation step, as it will not impact the result. Of course, in the evaluation of the interference between the cells and, for rate calculations, the presence of thermal noise is considered.

5. Role of Context-Information Databases

One of the key concepts that gains momentum in recent years in the domain of wireless networking is the efficient provision of access to dedicated databases that store various pieces of information about the environment [15]. We call them context-information databases, CI DB, and, in our case, such a database will be used by the central coordination entity used for network slicing management. The database may be populated with the following data defining the transmission context:

(i) a coverage map of the existing transmission (associated to the slices) that has to be protected from interference. The new slice has to be created in such a way that the existing transmissions are protected.

(ii) the specificity of each slice, such as the definitions of spectrum emission masks, possibly, approximations of the reception filter characteristics, historical values of computed ACIRs, and SIR.

(iii) past decisions to certain SP requests.

Having access to such information, the SIP may select the best transmit opportunity for each new slice. However, the way that the database is populated and the way the information should be stored is left for further study.

6. Simulation Results

In order to verify the performance of each proposed method, we have carried out extensive computer simulations in two

Table 1: Outage probabilities achieved for three proposed methods: use case 1.

Method	Outage probability			
	$(\xi, \omega) = (30,70)$	$(\xi, \omega) = (20,50)$	$(\xi, \omega) = (20,20)$	$(\xi, \omega) = (20,100)$
A	0.0950	0.1818	0.09504	0.0950
B	0.1178	0.1985	0.0214	0.2982
C	0.0840	0.1546	0.0840	0.0840

use cases, which are described below. The performance of the considered methods is measured twofold:

(i) First, by computing the fragmentation coefficient, i.e., after each frequency allocation we measure the value of the fragmentation coefficient and present it in the form of a Cumulative Density Function (CDF), which is equal to the probability that fragmentation coefficient μ is below some certain threshold μ_0, i.e., $\Pr(\mu < \mu_0)$. In the first use case, the fragmentation coefficient is measured per one base station, and, in the second use case, it is presented in various contexts (e.g., per entire network and per base station).

(ii) Second, by computing the outage probability, i.e., the probability of a situation that a new request for network slice creation is not realised due to the lack of resources.

6.1. Use Case 1: Single Base Station. In the first use case, we focus on network slicing within one separate base station; i.e., we assume that the SIP is in possession of one mast and offers the creation of various network slices using its resources. This particular example can be also understood as a case where each base station in a network is treated as an autonomous entity.

The simulation parameters have been set up as follows:

(i) The bandwidth of the considered spectrum for network slice allocation is set to $W = 10$ MHz, and the central frequency was set to 3.5 GHz (thus, the frequency range considered for simulation is from 3.45 GHz up to 3.55 GHz)

(ii) The band W is split into $C = 20$ channels, each of 500 kHz of bandwidth

(iii) The new process for appearance of a new request for network slice creation is modelled as an exponential one with the intensity of ξ assumed time units (i.e., the mean value was set to ξ time units); the definition of the slice duration (i.e., the time for which the slice is needed) is also realised as an exponential random variable with the mean value of ω time units; in this experiment we have verified the following cases: $(\xi, \omega) = \{(20,20), (20,50), (30,70)\}$,

(iv) The results have been collected over 100000 separate scheduler decisions runs, and the ultimate minimum requirement to stop the stimulation was the achievement of 1600 positive slice allocations in the whole simulation run

(v) The appearance of the requests for two considered network slices is equally probable.

The achieved results for three discussed methods are shown in Figure 1, where we compared the CDF of fragmentation coefficient μ for various setups of (ξ, ω). As the fragmentation coefficient should be maximised (i.e., we want to avoid the situation where the spectrum is highly fragmented), the performance of the tested method is better when, in simple terms, the CDF is shifted to the right in the plot.

One may observe that, for low and high values of μ_0, which corresponds to situations where the frequency spectrum is almost empty or fully loaded, respectively, all methods will achieve similar performance. The greatest performance improvement is observed in midrange of values of μ_0. The achieved results show that method C achieves usually the best results in the midrange of μ_0 regardless of the slice setup (ξ, ω). However, the most important conclusions from the achieved results are that the performance of the method significantly depends on the considered use cases. When the slice durations is relatively low (see Figure 1(c)) or high (see Figure 1(d)), the observed gain is rather negligible. Let us note that these results are achieved for the case when the noncontiguous waveform is not allowed for selection. As it will be observed in the following sections, the inclusion of these advanced schemes can lead to significant gains. Moreover, the CDF of fragmentation coefficient has to be analysed jointly with other metrics, such as outage probability—the achieved results are shown in Table 1. Outage probability reflects here the situation that there will be no resource allocated for a given slice. The value of this probability is calculated as the number of situations, where there was no resource allocated to a given slice over all simulation runs. One may observe that in three cases (i.e., for long slice duration) the worst performance is observed for method B, whereas the lowest outage probability is achieved mostly for method C. In other words, the outage probability will be minimised in such a scenario when the algorithm tends to minimise the spectrum fragmentation. Interestingly, in case when the slice duration is low, the best results are achieved for method B.

Let us notice that both results (CDF and outage probability) show the performance of the entire solution, i.e., waveform selection and resource allocation steps. However, our observations show that in the considered scheme the algorithm in most cases selects mainly OFDM as the optimal waveform, and the noncontiguous version of it was chosen rarely; thus the above figure as well as the table below rather shows the comparison of the three frequency allocation methods. In order to observe the impact of the waveform selection phase, we have analysed new use case no 3 (see

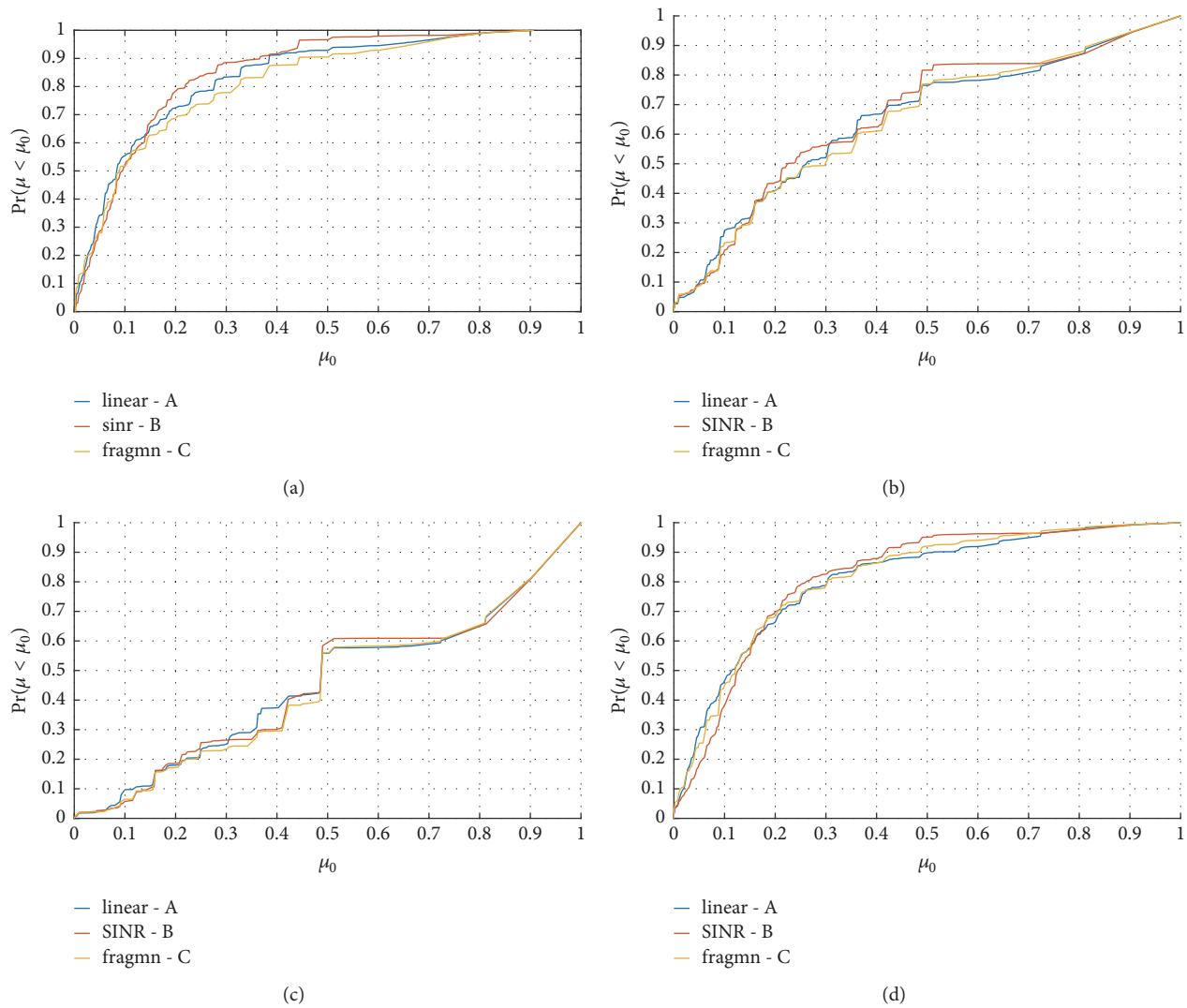

Figure 1: CDF of fragmentation coefficient observed at single station (both eMBB and mIOT slices can be deployed) for various setups of (ξ, ω): (a) $(20, 50)$, (b) $(30, 70)$, (c) $(20, 20)$, and (d) $(20, 100)$.

below), where the role of this phase of the proposed solution is dominant (please see the following section).

6.2. Use Case 2: Fragment of the Network. In the second use case, we are considering three base stations being part of a bigger network, as shown in Figure 2. We simulate the cells in the form of hexagonal regions and we assume that the potential interference originated from the outer cells (e.g., from the so-called first circle around this network fragment) is low enough to be excluded from computations. Such a simplification is tractable, as the presence of similar, low-power interference originated from the outer cell will have identical impact on all methods and does not influence the relations and correlations between the methods.

In order to adjust the three proposed methods to the new scenario, we have applied the following modifications when compared to the previous use case. Mainly, in order to make a frequency allocation decision, not only do SIR between adjacent systems in the frequency domain have to be considered (as it was done in the first use case) but also the requirements on resultant Signal to Interference plus Noise Ratio (SINR) values observed at the edges of the cell. Thus, the key extension of methods A, B, and C described above is that while allocating a certain frequency to the slice, the algorithm not only checks the SIR requirements but also computes the potential impact of the new frequency assignment on the SINR value observed at the cell edges. In practice, the SINR requirement has to be fulfilled at each point of the cell edge; in our simulation, however, we consider only selected points for evaluation, which are marked by red dots in Figure 2.

The simulation setup was in general the same as in the first use case, but the following additions have been included:

(i) as the SINR metric has to be computed, we assumed the propagation model defined in the WINNER project, which is designed for micro cell deployment in an urban scenario (so-called C2 option);

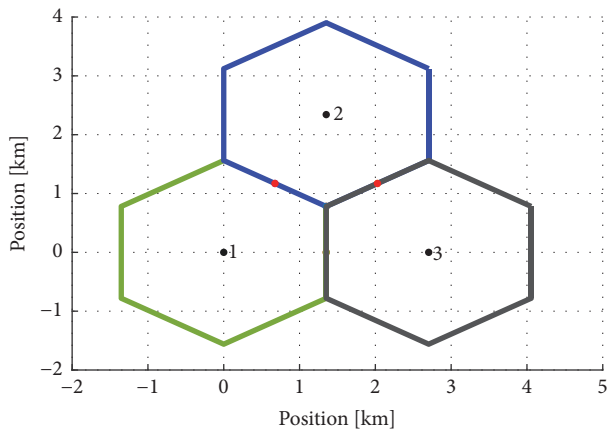

Figure 2: Topology of the considered fragment of the network.

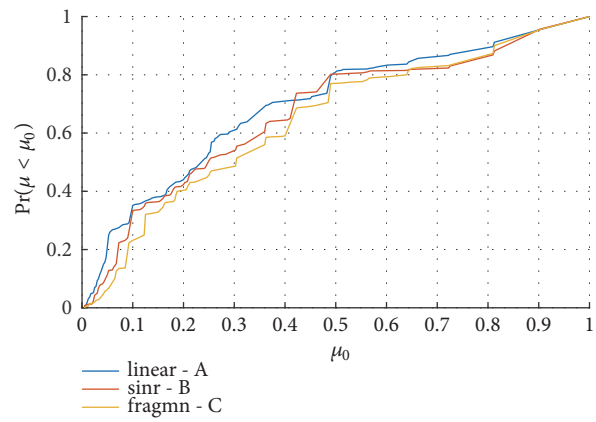

Figure 3: CDF of fragmentation coefficient observed at the first base station (both eMBB and mIOT slices can be deployed).

(ii) furthermore, the base station and end-user terminal are assumed to be deployed at the heights of 30 m and 2 m, respectively;

(iii) we assume that in both slices the transmit power is fixed and the power spectral density is set to 0 dBm per 5 MHz;

(iv) noise power was calculated for the temperature of 20 degrees Celsius;

(v) the cell edge contour is defined by the line where the observed SNR is equal to 5 dB over thermal noise; thus in the given scenario, the cell radius was equal to approximately 1.56 km;

(vi) the required SIR level between any two systems in the frequency domain was set to 26 dB;

(vii) and, finally, the required observable worst case SINR level, measured in the four positions marked in Figure 2 by black dots, is to be above -1dB.

Moreover, we have assumed that all base stations are technically capable to deploy slices of eMBB traffic type, but only two of them are able to generate signal suitable for the mIOT slice. In other words, a mIOT network slice may be created only over two base stations, whereas an eMBB network slice may be created over the entire network. Such a scheme is selected to illustrate the flexibility of slice creation; i.e., the tenant (SP) may be interested in delivering its services only in some specific area, and the SIP has to manage all requests for slice creation coming from all tenants. In consequence, when a new request for network slice creation appears, the algorithm tries to create the network slice over the entire area that supports slices of a given type. Such a need generates some new design issues; i.e., due to the mutual interference between the adjacent cells, the same frequency resources cannot be typically applied over the network area. The entire problem of frequency allocation now becomes highly similar to various solutions from the domain of frequency planning.

The achieved results ale plotted in Figures 3, 4, and 5, where the CDFs of fragmentation coefficients are shown per each base station and in Figure 6, where the CDF is calculated for the entire network. By analysing these figures one may

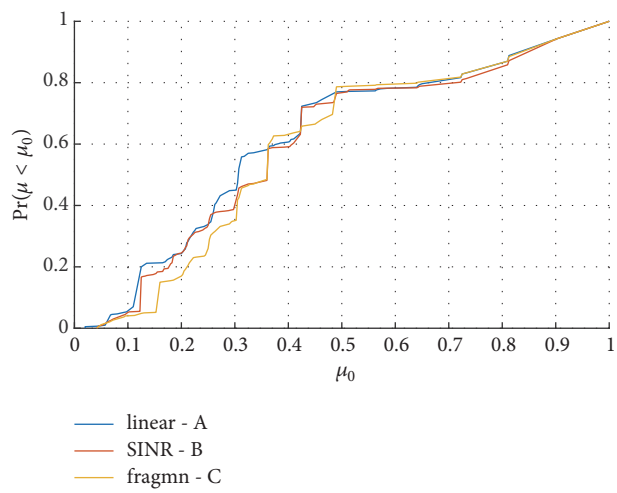

Figure 4: CDF of fragmentation coefficient observed at the second base station (both eMBB and mIOT slices can be deployed).

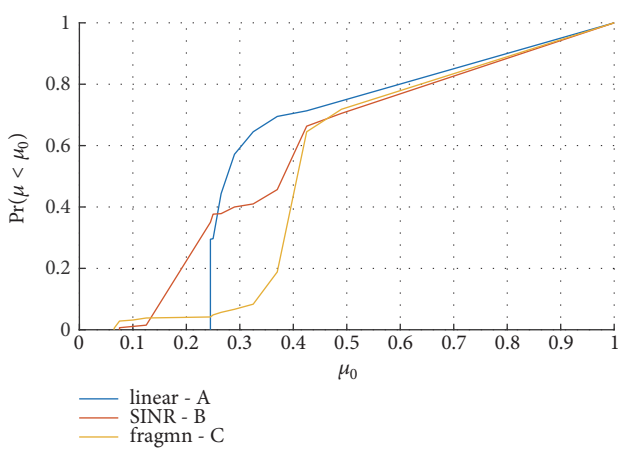

Figure 5: CDF of fragmentation coefficient observed at the third base station (only eMBB slice can be deployed).

Table 2: Outage probabilities achieved for three proposed methods, use case 2.

Method	Base station 1	Base station 2	Base station 3	Network	eMBB Slice	mIOT Slice
A	0.1392	0.2975	0.6429	0.3075	0.4405	0.0811
B	0.1456	0.2975	0.6548	0.3125	0.4643	0.0541
C	0.1435	0.3017	0.6310	0.3083	0.4537	0.0608

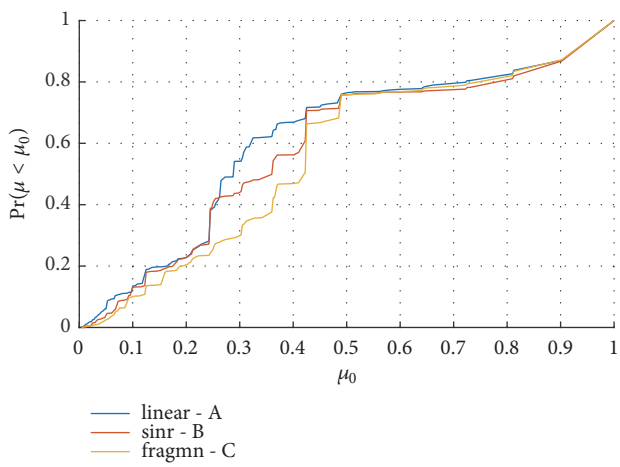

Figure 6: CDF of fragmentation coefficient observed from the network perspective.

observe that, first, in all cases, method C again achieves the best performance in terms of fragmentation and, again for low and high values of μ_0, all methods achieve similar results.

It is also good to analyse the observed outage probability in the network use case. In Table 2 we showed the achieved values in various configurations, mainly, per base station (i.e., the probability that certain base station will be in outage), per slice, and for the entire network. Surprisingly, in a multicell scenario, the achieved values of observed outage probability are almost equal, and the differences between the methods tend to be statistically insignificant. Moreover, the values themselves are high and cannot be accepted in practical situations. This is mainly due to the fact that in the considered use case the algorithm very often cannot allocate the resource regardless of the selected waveform and chosen resource allocation scheme. The mutual constraints between the neighbouring cells and the need for maximisation of the coverage area by a given slice also have a direct impact on the achieved values. Finally, please note that in our solution we have applied a greedy approach, which can be significantly improved.

6.3. Use Case 3: Dominance of the Waveform Selection Phase. In the previous scenarios we have observed the performance of the two-phase algorithm, and one may question the real impact of the waveform selection phase on the final performance. In order to highlight the importance of this step, we have verified the performance of the proposed solution in a scenario with limited resources. The simulation setup applied in this use case is the same as in the first one; however we assume that

(i) there three types of slices: one for mIOT traffic (where the GMSK modulation is applied and which is allocated for time significantly longer than other slices), one slice for eMBB traffic (where only OFDM waveform can be selected), and one for URLLC traffic (where either OFDM or NC-OFDM can be selected).

(ii) for the eMBB slice the appearance of new network slice request was modelled as exponential process with mean value set to 50 time units and with duration also modelled as random variable with exponential distribution with mean value of 50 time units,

(iii) for the URLLC slice the appearance of new network slice request was modelled as exponential process with mean value set to 20 time units and with duration also modelled as random variable with exponential distribution with mean value of 20 time units,

(iv) the SIP offered C=15 channels of 500 kHz of bandwidth

(v) the eMBB and URLLC slices requested 6 channels each (3 MHz in total for each slice) whereas mIOT slice requested just one channel (500 kHz).

(vi) GMSK signal is present in the fifth channel.

One may observe that in such a scenario only six different frequency allocations are possible for the three considered methods, as indicated in Figure 7, where the allocation indexed with 1 represents the initial stage; i.e., there is a long-term running mIOT slice. In the considered scenario, once the eMBB slice is allocated, it is not possible to allocate the new eMBB slice. At the same time, the new URLLC slice, which accepts more advanced waveforms, may be allocated even if there is already one eMBB or URLLC slice. Furthermore, there is a gap between mIOT slice and other OFDM-bases slices due to the need of minimising the interslice interference. We have also assumed that there is no need for a gap between two OFDM slices as discussed in the interference analysis section. One may observe that situations 2, 3, and 4 will be achieved by methods B and C whereas 5, 6, and 7 will be achieved only by method A.

For this situation we have achieved the outage probabilities of 0.4549 and 0.1567 for eMBB and URLLC slices, respectively (of course, the outage probability for mIOT slice is zero). As the number of possible combinations of slice allocation is highly limited, the final performance is affected mainly by the waveform selection phase. In consequence, the achieved outage probability is almost the same for each method (A, B, and C). One may observe that the URLLC slice, which has an option for NC-OFDM waveform, achieves significantly lower outage probability when compared to the

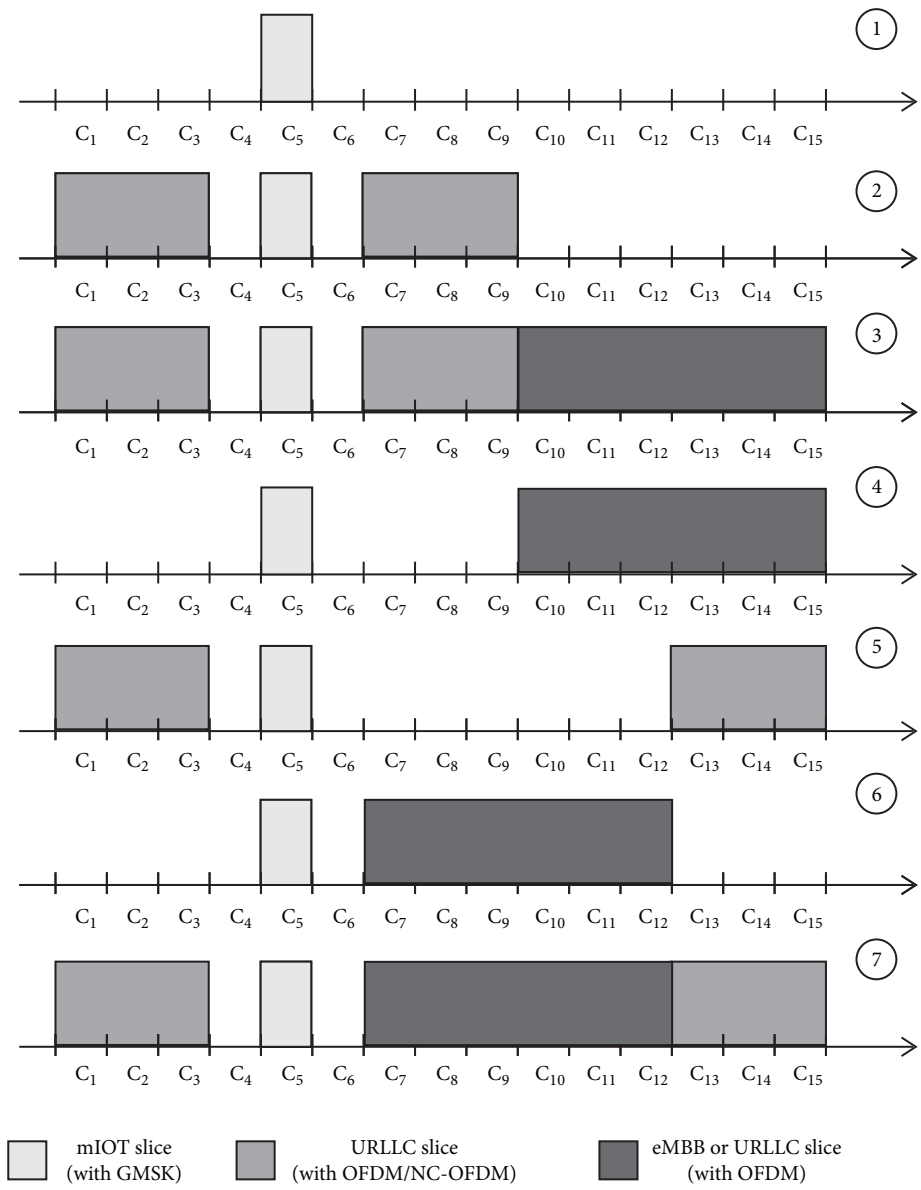

Figure 7: Possible slice allocations.

eMBB slice. This is because the ability to choose noncontiguous waveform creates the opportunity for the assignment of noncontiguous resources. Because there are only six values of the fragmentation coefficient, the CDF of fragmentation coefficient does not provide any new technical insight; in consequence it is not shown here.

6.4. Use Case 4: Single Base Station with Three Slices. Finally, we decided to analyse the performance of the proposed method, when there are three different types of slices available in the single base station, i.e., mIOT, eMBB, and URLLC. In general, the same setup as for use case 1 has been selected; mainly the band $W = 10$ MHz is split into $C = 20$ channels, each of 500 kHz of bandwidth. Moreover, the appearance and duration of each slice was modelled with exponential distribution with different intensities; i.e., eMBB slice (OFDM only, 3 MHz band) has intensity of appearance set to 50 time units (mean value of the exponential distribution) and duration set to 50 time units, URLLC slice (OFDM only, 3 MHz band)–5 and 20 time units, respectively, and mIOT (GMSK, 0.5 MHz band)–20 and 50. Finally, the probability of occurrence of the new slice was set to 0.3 for eMBB and URLLC and 0.4 for mIOT. The results have been achieved over 100000 decisions.

First, let us present the CDF of the fragmentation coefficient (Figure 8). Although the best results are still achieved for method C (especially in the range from 0.3 to 0.5), the differences between these methods are not that significant. We claim that the value of fragmentation coefficient highly depends on the intensities of each slice generation process. Although the differences in the CDF are not that significant, the achieved values of outage probability prove that method

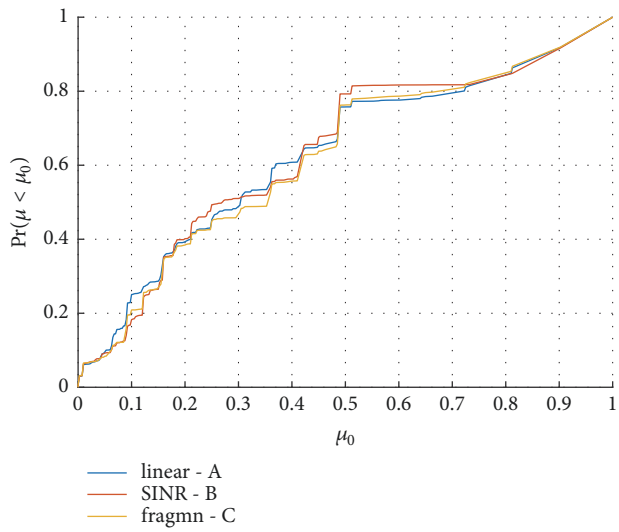

Figure 8: CDF of fragmentation coefficient observed from the network perspective.

Table 3: Achieved outage probabilities achieved for three slices.

Method	Network	mIOT slice	eMBB Slice	URLLC Slice
A	0.1048	0.0047	0.0851	0.2578
B	0.1296	0.0025	0.1102	0.3182
C	0.0955	0.0026	0.0759	0.2387

C (i.e., the one which is optimal from the point of view of the spectrum fragmentation) guarantees the best results, as shown in Table 3. It may be observed that the overall base station performance is mostly dominated by the most frequent slice, i.e., the one that appears with mean value set to 5 time units. As for this slice six channels are requested, it happens quite often that no resources may be allocated to this slice. It shows, however, that such a greedy approach results in unacceptably high outage probability for URLLC slice, where the strict requirements for end-to-end delay are defined. Thus, probably, in the future some kind of priorities shall be defined, and advanced optimisation procedures shall be applied.

7. Summary and Conclusion

In our work we have discussed the possibility of applying the waveform flexibility concept with adaptive spectrum resource assignment to network slicing. The proposed heuristic algorithms for waveform selection and frequency assignment are designed to maximise the revenue of the spectrum and infrastructure provider under the constraint that the assumed quality of service metrics per each slice is guaranteed. Thus, in the first step, which is common for all proposed algorithms, we decided to select such a waveform that, on the one hand, fulfils all requirements specified for the certain network slice (e.g., minimum rate) and, on the other, minimises energy consumption required for data processing. In a nutshell, at all times the simplest possible waveform is selected. Next, once the waveform is selected and the corresponding bandwidth is known, three various approaches to frequency assignment have been tested. The performance of these methods has been verified in four simulation use cases. The obtained results present the performance of these methods indicating that there are ways to optimise the spectrum fragmentation. It has to be stated that the results highly depend on various parameters (such as traffic intensity and definition of the slice in terms of physical and medium access control layers), and thus further investigations toward minimisation of spectrum fragmentation are possible. In a nutshell, however, the results presented in this work prove that there is a possibility of flexible and adaptive resource assignment that would be highly helpful in the practical implementation of network slice concept.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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