



## Spectrum for Private Networks

### *Challenges and Opportunities - A Case Study based on Danish Regulation*

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## RESEARCH ARTICLE

# Spectrum for Private Networks: Challenges and Opportunities—A Case Study Based on Danish Regulation

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**ABSTRACT** This paper investigates the challenges and opportunities for assigning spectrum for private 5G networks, with particular emphasis on the 3.5 GHz band and regulation issued by the Danish spectrum authority Energistyrelsen. We are chiefly interested in the dilemma between providing sufficient and clean spectrum for a private network versus ensuring that high network density can be supported. Indoor and outdoor scenarios are considered, and the performance impact of interference on different levels of service availability are investigated. We develop and propose new solutions for enhanced spectrum regulation options leveraging native 5G features, such as bandwidth part, to support denser outdoor and indoor deployments that can enhance best effort traffic and simultaneously protect spectrum for critical and delay sensitive traffic. System-level simulations show that our proposals can protect critical services and significantly increase the capacity per network in dense deployments.

**INDEX TERMS** 5G private networks, spectrum regulation, spectrum sharing.

## I. INTRODUCTION

Private wireless networks based on cellular technologies will play a pivotal role in the digital transformation of various vertical sectors. As a notable example, 5G New Radio (NR) offers significant features and benefits for critical applications compared to unlicensed band technologies, where mobility and unpredictable interference pose several challenges [1], [2]. While private networks can be provided as a network slice by re-using spectrum from a public 5G network operator, many private industries may require or favor the operation of a stand-alone non-public network (SNPN) using their own spectrum. However, the timely and localized availability of sufficient spectrum for exclusive use is

a challenging prerequisite when one considers the envisioned large number of private stakeholders [3].

In Europe, spectrum regulators have begun to secure affordable and locally licensed spectrum for private 5G networks, intended for a wide range of use-cases such as smaller companies, factories, ports, hospitals, and agriculture [4], [5]. In particular, the 3.5 GHz band is in focus, as it offers a combination of significant bandwidth and good coverage properties. Most regulations are based on a first-come, first-served basis, and interference between networks is managed by defining maximum signal interference levels at the edge of the service area, potentially with some exclusion zones. If tenants can agree, they may jointly decide to reduce such restrictions. In Denmark, for example, the recommended exclusion zone is 500 m, defined from the private network's service boundary [6]. In practice, this means that only a very low density of private networks can be supported given

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available frequency allocations and the spectrum needs of individual networks.

The challenge of allowing high spectrum re-use among dense private networks is a widely researched topic. The work in [7] analyzed the existing spectrum valuation approaches and expanded spectrum valuation to cover local 5G networks in shared spectrum bands. In [8] the authors discuss private industrial network requirements and defined a framework that can be used to assess the feasibility of the spectrum management approaches in several countries, yet no simulation results were provided. The increasing role of spectrum sharing in accommodating new 6G systems with incumbents is discussed in [9]. Finally, [10] provides a brief overview of the regulatory framework concerning dynamic spectrum sharing in Europe and the US based on automated and centralized spectrum management schemes. Europe has trialed [11]–[13] the Licensed Shared Access (LSA) framework specified by ETSI Reconfigurable Radio Systems (RRS), but neither LSA nor its enhanced version eLSA have seen any adoption to date. In the US, automated spectrum access management via Spectrum Access System (SAS) has been successfully commercialized for the Citizens Broadband Radio Service (CBRS) band, which stretches between 3550–3700 MHz. However, the CBRS SAS is meant to protect incumbents and high-tier tenants but it is not designed to maximize spectral efficiency. It should be noted that the Automated Frequency Control (AFC) framework under discussion for the US 6 GHz band also targets incumbent protection, albeit in a much simpler manner than CBRS SAS due to the nature of the incumbents. The practical challenges and open issues associated with current automated spectrum management schemes are highlighted in [14].

While advanced management schemes are under research and trial, ongoing spectrum regulation in Europe for private networks, in ex. the 3.5–4.2 GHz, takes a much simpler approach. Germany opened 100 MHz in the 3700–3800 MHz band for use by private networks in 2019 [15] and private networks must ensure interference free operation by protecting existing private networks and users in the band. Ofcom, in the United Kingdom, offers two different license types on a first-come, first-served basis: shared access and local access licenses. The local access license can be granted in geographical regions where it is not in use by the operator. The shared access licence comes in two versions; “low power”, which allows multiple base stations with maximum equivalent isotropic radiated power (EIRP) of 24 dBm within a circular area of 50 m radius. The other is “medium power”, which allows a base station at a single location with a maximum EIRP of 42 dBm [16]. Ofcom further documents the requirements of antenna heights and maximum base station powers in the various available bands as well as whether indoor only or outdoor coverage is allowed.

In this paper, we focus on spectrum management techniques more in line with methods taken into use in ex. Denmark, UK and Germany. We will focus specifically on the Danish spectrum regulation, which applies for the

3740–3800 MHz band. The contribution of this paper is relevant when considering extending the regulation to cover the 3.8–4.2 GHz band in coming years. Our approach is novel in the sense that we consider specifically the performance based on achieved service levels such as minimum end-user data rates for the networks, ex. ensuring availability which is typically required from critical private networks. Besides assessing the effectiveness and scalability of the current regulation, we formulate and provide a numerical analysis of practical innovations for improved spectrum regulation leveraging state-of-the-art 5G capabilities such as bandwidth parts (BWP) to support a higher density of private networks without jeopardizing performance.

Next, Section II details the spectrum and regulation of private wireless networks in Denmark. Then Sections III and IV introduce the system model and simulation methodology used as baseline for the quantitative performance results discussed in Section V. Simulations are the chosen methodology due to the high complexity of the system model and our desire to produce results with high degree of realism, which otherwise would be sacrificed if attempting simpler theoretical performance analysis. We adopt the widely accepted 3GPP methodology guidelines and modeling assumptions for system-level simulations. Section VI presents a new design and performance study of our BWP inspired solution for increasing density/capacity in dense deployments. Section VII concludes the paper.

## II. DANISH REGULATION FOR PRIVATE NETWORKS

In Denmark, the spectrum auction in 2020 included the 3500 MHz bands. An allocation of 140 MHz was awarded to the Telia-and-Telenor-owned radio access network “TT-network”, where the upper 60 MHz from 3740 MHz to 3800 MHz comes with a rental obligation to catalyze the establishment of private networks [6]. The spectrum, similarly to other EU countries, is granted by the operator to so-called vertical sectors (transport, media, manufacturing, etc.) on a first-come, first-served basis. Each vertical incumbent is granted spectrum for the applied property, plus a 500m exclusion zone in all directions. In practice, this means that the borders of any two given networks with overlapping frequencies will be separated by a minimum distance of 1 km. The gNB transmit powers are not strictly regulated, as long as the Power Flux Density (PFD) at the border of the exclusion zone does not exceed the  $-5 \text{ dBm/m}^2/5\text{MHz}$  limit. In order to protect networks in adjacent frequencies, networks are required to synchronize to a common TDD pattern, regardless of what uplink and downlink traffic is present in the private network.

In Denmark, like other European countries, the annual price to lease the spectrum is relatively low. For example, leasing 50 MHz for a circular service area of  $5 \text{ km}^2$  costs approximately €460 annually. With such a low entry barrier, the practical challenge and limiting factor to the widespread deployment of private 5G networks is the 500 m exclusion

zone. In our example, the total effective leased area becomes  $9.75 \text{ km}^2$ .

The Danish regulation does not differentiate between gNB power classes or between indoor and outdoor deployments, and per case exemption from the recommended exclusion zone and power classes is required.

### III. SYSTEM MODEL

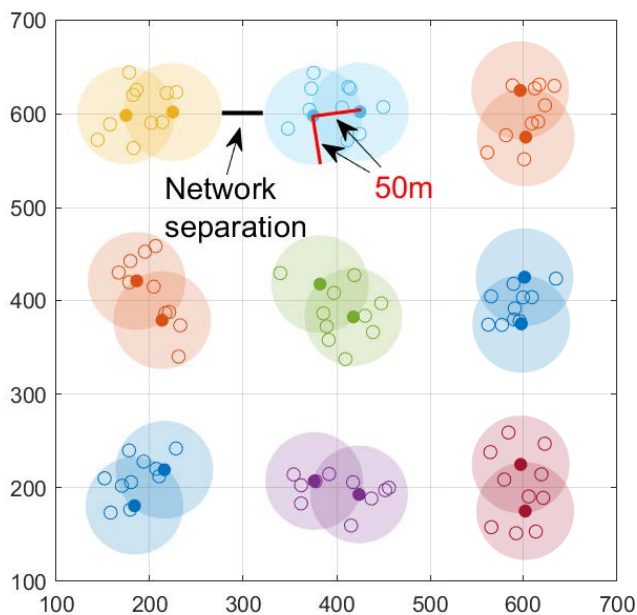
In this study we consider dense deployments ( $\leq 500 \text{ m}$  regulated exclusion zone), ex. in sub-urban and urban areas, and assume micro-grade network equipment with a maximum transmit power of  $30 \text{ dBm}$ . To study a hostile interference environment, we place 9 identically configured private networks in a square grid as illustrated in Fig. 1. Each network consists of two base stations (gNBs) separated by  $50 \text{ m}$ , each with a circular service area with radius of  $50 \text{ m}$ . The reason to assume two gNBs per network, is to ensure that advanced interference rejection capabilities of the UE will be already used within the network and not to null out interference from other networks, i.e. seeking the most difficult scenario. Five users are randomly dropped in the service area per gNB, totalling 10 user equipments (UEs) per network. All gNBs are assumed to be  $5\text{G NR}$  centred at  $3.5 \text{ GHz}$  and configured to the same overlapping  $90 \text{ MHz}$  bandwidth. The square grid of nine networks is considered in two different coverage and propagation scenarios, one outdoor and one where all networks are located indoors in separate buildings. In both scenarios, the inter-network distance is varied to evaluate the performance degradation of the resulting interference from neighbouring networks. These deployment types are detailed in the following.

#### A. SQUARE GRID LAYOUT - OUTDOOR DEPLOYMENT

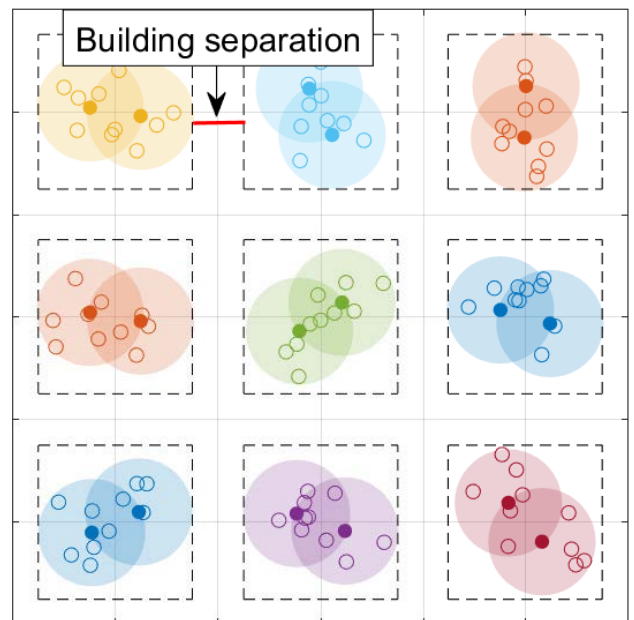
In the outdoor deployment scenario, each of the nine networks has a fixed service area radius and number of users with full buffer traffic. The network separation is the combined exclusion zone of both networks, and is measured as the minimum distance between two neighbouring networks' service area borders, as illustrated in Fig. 1. Within a private network, the two gNBs are separated by  $50 \text{ m}$ , each with a  $50 \text{ m}$  service area radius, meaning there is a maximum of  $75 \text{ m}$  from the network center to the edge of the service area. Placing the networks with a network separation of  $X \text{ m}$  is achieved by fixing the distance between the networks centre as  $75 \text{ m} + X \text{ m} + 75 \text{ m}$ . Due to the random alignment of a networks two gNBs and the resulting shape of the service area, network separation between certain networks can be slightly larger than the specified minimum distance  $X \text{ m}$ . The network separation ranges from negative  $100 \text{ m}$  up to  $1000 \text{ m}$ , where a negative value indicates an overlap of two neighbouring networks service areas.

#### B. SQUARE GRID LAYOUT - INDOOR DEPLOYMENT

In this scenario, all of the networks and their service areas are located indoors, and there are a minimum of two external walls between any UE/gNB from separate networks. The same network service area and configuration as outdoor is re-used here, but placed inside  $125 \text{ m} \times 125 \text{ m}$  buildings as depicted in Fig. 2. The external wall penetration loss is set conservatively to not overestimate the performance, at  $10 \text{ dB}$  per wall [17], [18]. The considered distances between the external building walls range from " $0 \text{ m}$ " and up to  $350 \text{ m}$ . As the size of the building just extends to the furthest point of



**FIGURE 1.** Nine networks deployed in simulation, 2 gNBs and 10 UEs per network. Network gNB-gNB distance =  $50 \text{ m}$ , gNB service area radius =  $50 \text{ m}$ .



**FIGURE 2.** Indoor Deployment, each networks two base stations and UEs are located inside  $125 \times 125 \text{ m}$  buildings (dotted lines).

the service area, the building separation is equivalent to the network separation in the outdoor case in Fig. 1.

### C. OPTIMIZATION CRITERIA

The optimization goal is to ensure the best spectral efficiency among participating private networks, but with the mindset that spectrum is a shared resource. As we consider private networks, we also consider the need to have a performance guarantee for ex. critical traffic. To investigate the achieved performance, we therefore consider each network's performance by collecting the average user throughput for users within the networks and combining them into per-network empirical cumulative distribution function (CDF). To consider the needs for guaranteed network performance, four different outage percentiles of the CDF are considered, measuring the minimum throughput among 50, 90, 95, or 99% of the total number of UEs.

### IV. SIMULATION ASSUMPTION AND METHODOLOGY

The results are based on an advanced in-house developed system-level simulator using the Monte Carlo method. We adopt the agreed 3GPP industry standard methodology and modelling assumptions for 5G NR dynamic system-level simulations as also adopted in the following research studies [19]–[22], where additional details are available. The system level simulator is designed to model the multi-user and multi-cell deployments under advanced channel propagation conditions and includes stochastic channel models calibrated against similar models used in 3GPP. The simulator models the majority of the PHY and MAC layer procedures in line with 3GPP guidelines with great detail. It covers, among others, dynamically scheduled users in the time-frequency domain, periodic channel state feedback (CSI) reporting to select optimal modulation and coding scheme (MCS) for a target block-error rate (BLER), and usage of hybrid automatic repeat request (HARQ) feedback in case of decoding failures. All simulations are carried out with multiple realizations, each with randomized network orientation and user drops to achieve sufficient and statistically stable data points. Results from each realisation of a given network separation is combined afterwards. Full buffer traffic model is used to simulate a worst-case interference scenario and corresponding impacts on the achievable throughput. For every user, an average throughput sample of each realisation of a given network separation are collected for an empirical cumulative distribution function (CDF). This empirical CDF will measure the minimum guaranteed user throughput for a specific service availability or outage level.

A summary of the key simulation assumptions are shown in Table 1. Both UE and base station have two antennas, but are limited to single stream transmission in both uplink and downlink. UEs are configured with a Minimum Mean Square Error - Interference Rejection Combining (MMSE-IRC) receiver and can cancel up to 1 interfering signal [23], [24]. All networks share the regulations recommended configuration of 30 kHz sub carrier spacing (SCS) with

**TABLE 1. Key parameters of system level simulations.**

Parameter	Assumption
Carrier frequency	3.5 GHz
Bandwidth	90/100 MHz
PHY numerology	30 kHz subcarrier spacing
Transmission Time Interval (TTI)	14 OFDM symbols
Duplexing mode	Time division duplexing (TDD)
gNB transmitter	Ntx = 2 antennas
gNB transmit power	30 dBm
gNB antenna Gain	9 dBi
gNBs per network	2
UE distribution	Uniformly distributed, 5 UEs per cell
UE receiver	Nrx = 2 isotropic antennas MMSE IRC receiver
Network gNB-gNB separation	50 m
gNB service radius	50 m
Frame format	DDDSU
Traffic model	Full buffer
Channel model outdoor	3D Urban-micro
Channel model indoor	modified COST 231 multi-wall model
External wall penetration loss	10 dB
UL power control	$P_0 = -90$ dBm, $\alpha = 1$
Scheduling (UL & DL)	Proportional fair (time and frequency) Max Scheduled Users = 5/TTI
Link adaptation	Inner and outer loop, 10% BLER target
HARQ	Async HARQ, incremental redundancy
Mobility	Static, fast-fading speed: 3 km/h

synchronised and static TDD frame structure of 'DDDSU'. Where 'D' and 'U' corresponds to a downlink and uplink slot of 14 OFDM symbols, respectively. The 'S' consists of 10 downlink, 2 guard, and lastly 2 uplink symbols. Uplink power control has been optimised for the current network size and configuration to  $P_0 = -90$  dBm and  $\alpha = 1$ . The outdoor only environment uses the 3D UMi channel model. The indoor scenario uses 3D UMi + the additional loss per wall in case the nodes are not located in the same building. If the nodes are in the same building, indoor propagation loss is considered by the modified COST 231 multi-wall model [25].

### V. PERFORMANCE RESULTS

Fig. 3 represents the empirical CDF of average simulated user throughput for four different network separations in the outdoor scenario. Starting with  $-100$  m, i.e. overlapping service area, there is a large amount of the users with very low average throughput. As expected, once the separation among networks increases, the interference conditions are improved and the resulting CDF shows a lower percentage of users in a low throughput condition.

Fig. 4 depicts the guaranteed user throughput for 50, 90, 95, and 99% of users. The throughput performance is considered to be converging when further increases in network separation only adds minor or no increase in throughput performance. The downlink performance converges at different distances of network separation, with 50% converged already at 0 m and 99% converging at approximately 800 m. If the regulated exclusion zone is aimed at guaranteeing one of these downlink service availability levels, the added exclusion zone to each networks service area would in this worst-case outdoor example be 0, 100, 150, or 400m. The uplink performance results in Fig. 5 shows a different sensitivity to interference



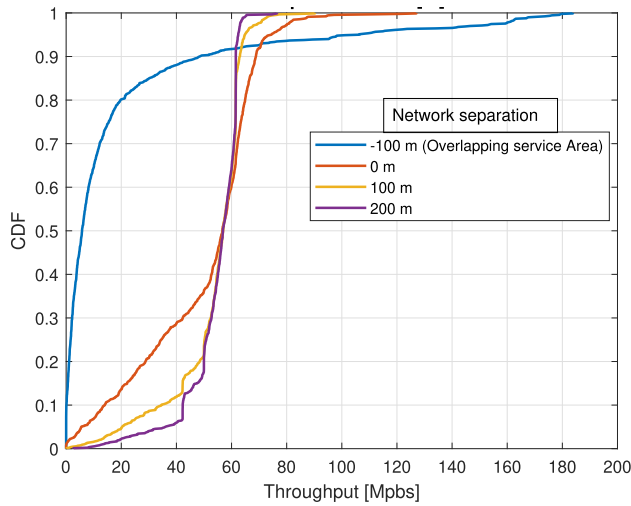


FIGURE 3. CDF of user throughput for X[m] network separation (Outdoor).

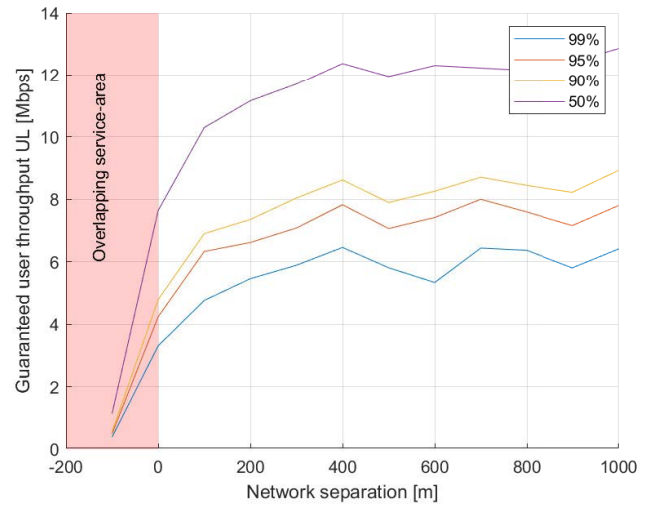


FIGURE 5. Service availability vs network separation (Uplink).

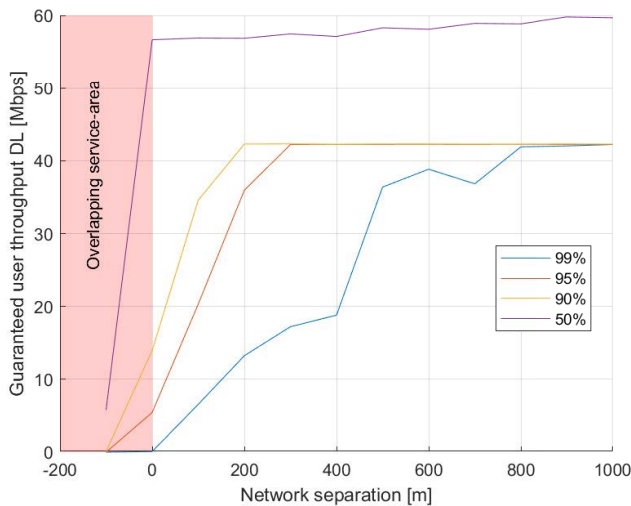


FIGURE 4. Service availability vs network separation (Downlink).

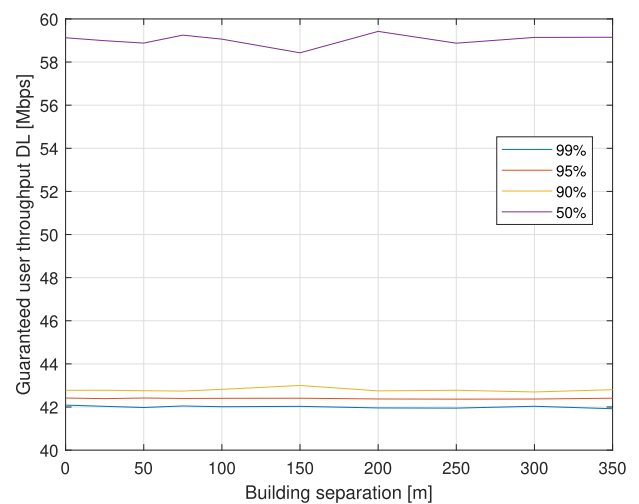


FIGURE 6. Service availability vs building separation (Downlink).

due to power control in the uplink, with all four service levels converging at approximately 200-400 m. This would require 100-200 m of exclusion zone added to each property with granted spectrum to guarantee any of the four service availability levels in uplink performance.

In Fig. 6, the downlink performance in indoor deployment does not indicate any sign of performance degradation with decreased building separation. The same is true for the indoor uplink results in Fig. 7. This demonstrates that indoor private networks can coexist without interference degrading the performance already with 10 dB external wall penetration losses and very dense deployments. Different industrial or modern building types can be expected to have at least 10 dB, but are more likely to have much higher penetration loss in external walls, leading to even better isolation of the networks.

The outdoor scenario where all nine networks share all of the available 90 MHz bandwidth considered so far is equivalent to no frequency planning; i.e. full reuse. This scheme

offers each network the highest possible throughput, given that networks have sufficient isolation from mutual interference e.g. 300m for 95% of users (Fig.4). To reduce the interference in dense deployments, the available spectrum can be divided such that each network gets its own exclusive 10 MHz bandwidth, equivalent to a 1/N frequency reuse. While this greatly improves the interference conditions, the total bandwidth and capacity per network is now reduced significantly. That means there is a significant trade-off between securing high quality access with high reliability and basic capacity for best-effort services.

## VI. TWO-TIER BANDWIDTH ALLOCATION SCHEME

We next consider a scenario where each network has a certain minimum requirement for guaranteed data rate (critical data capacity) while being interested in maximizing their average available capacity (best effort capacity). An example of this concept is shown in Fig.8, where neighbouring networks are

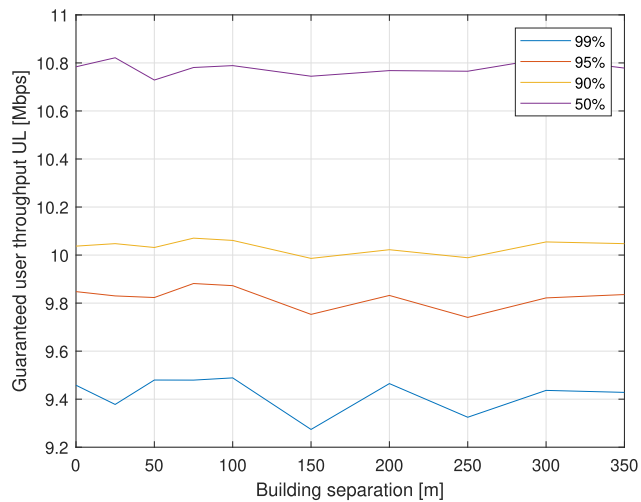


FIGURE 7. Service availability vs building separation (Uplink).

all allocated and share the same large spectrum chunk for best effort traffic. They are also allocated a smaller exclusive spectrum chunk for protected access of critical services. Both of these chunks can now be based on maximizing the joint capacity using the results in the previous section for ex. 50 and 99 percentile performance capacities. The larger spectrum chunk intended for best-effort traffic can be reused among networks with low inter-network distance for high spectrum utilization due to the more relaxed requirements. While the smaller spectrum chunk intended for critical traffic has a much larger reuse distance of minimum 1000 m network separation for protected and reliable access. Networks with outdoor coverage can then be deployed more densely, while having sufficient spectrum and good conditions for both traffic types.

The proposed spectrum allocation scheme can be realised by using the 5G bandwidth-parts (BWP) feature [20]. With BWP, a UE can be configured to operate on a limited and confined part of an NR carrier in both uplink and downlink. We make use of the BWP feature by first configuring each network with two separate spectrum chunks within the same NR carrier: a large spectrum chunk to serve best-effort, non critical traffic, and a smaller one for critical and delay sensitive traffic. One BWP would define the BWP scheme and handle information broadcast channels as well as paging operations etc. The other would only have broadcast channels to allow measurements, and the scheduler decides which UE sees which BWP combination.

To analyze this concept, simulations are run with a total simulated bandwidth of 100 MHz and a SCS of 15 kHz to share among the nine networks. The orange line in Fig. 9 illustrates the average cell throughput in an outdoor scenario when the frequency reuse distance is  $>1000$  m as required by the Danish spectrum regulation. In order to achieve this, when the network separation is between 100 m and 500 m, each network is allocated 10 MHz of spectrum (no reuse).

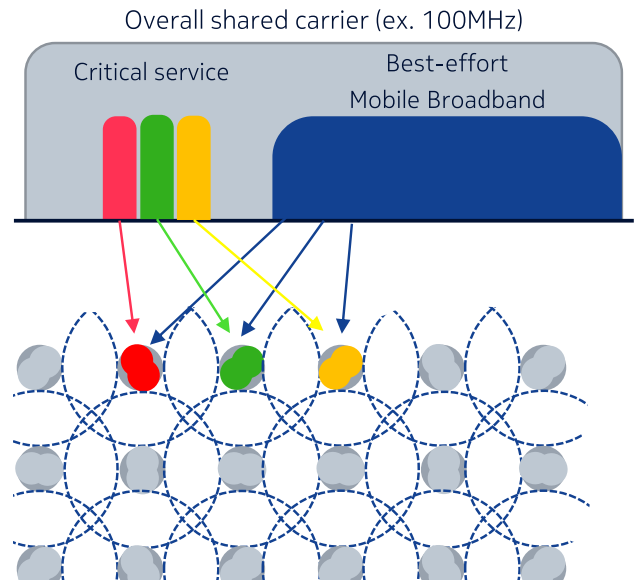


FIGURE 8. Allocation of exclusive spectrum for critical use (red, green and orange), to each network. And allocation of shared spectrum chunk for best effort (blue).

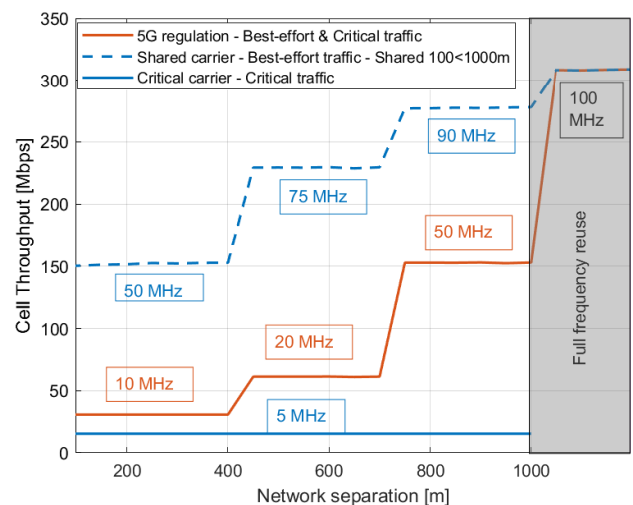


FIGURE 9. Two-carrier (BWP) allocation capacity per network (cell). Each networks spectrum allocation is written in orange (single allocation, current regulation) and blue (two allocations per network).

For network separations in the range 500 m - 750 m, the spectrum can be reused between certain networks, and each network is allocated 20 MHz. When the network separation is between 750 m and 1000 m, a frequency reuse factor of 2 is sufficient to achieve the necessary distance, and each network is allocated 50 MHz of spectrum. For network separation above 1000 m, every network is allocated the full 100 MHz spectrum.

By using the BWP feature to separate critical and best effort traffic, one large spectrum chunk with shorter reuse distance is required for the BE traffic. The throughput is nearly converged for 90% service availability already at 100 m network separation, as shown in Fig. 4. Therefore, in the example in Fig. 9, we assume a minimum of 100 m network

separation to use this frequency allocation scheme. In Fig. 9, the blue line represents the average cell throughput from allocation to critical traffic, while the dashed blue line plots the average cell throughput in the allocation for best effort traffic. For network separations between 100 m and 500 m, 45 MHz, i.e. 9 chunks of 5 MHz spectrum are required to satisfy reuse distances above 1000 m for critical allocation to all nine networks. The remaining 50(55) MHz is allocated for best effort, and shared by all networks. Similar to the orange curve, larger network separations means certain network can reuse spectrum, and fewer chunks of 5 MHz is required to satisfy the reuse distance, leaving more spectrum for the allocation towards best effort traffic. Network separations between 500 m - 750 m, and 750 m - 1000 m requires 5 and 2 chunks of 5 MHz respectively, to satisfy the 1000 m reuse distance for critical allocations, leaving 75 and 90 MHz for shared allocations towards BE traffic. Above 1000 m every network is allocated the full 100 MHz bandwidth.

As can be seen in Fig. 9, a cell throughput of 150 Mbps can be achieved at a much higher network density using the proposed spectrum allocation strategy that makes use of the NR BWP feature, while also offering the same protection of critical traffic resources. The portion of spectrum reserved for critical traffic can be increased if required, by sacrificing some of the best-effort throughput for more exclusive spectrum to each network.

## VII. CONCLUSION

We have evaluated the performance of private networks in shared spectrum using the Danish 3.5 GHz regulation as a starting point. The recommended exclusion zone of 500 m per network and the power flux density restriction of  $-5 \text{ dBm/m}^2/5\text{MHz}$  at the edge of the exclusion zones protect the private networks effectively. Specifically, co-channel outdoor networks are able to achieve service availability above 99% by following the Danish guidelines. However, the density of private networks can be increased by 5-8 times if the network separation is reduced to 200-300 m, still ensuring a 90-95% service availability. For indoor deployments, our results show that the performance impact from interfering networks is negligible for typical wall penetration losses. As a result, we recommend that the regulation recognises (i) the difference between indoor and outdoor deployments and (ii) their maximum transmit powers. These two aspects have a major impact on the required network separation and, in turn, the spectrum utilization and access for new leases. Secondly, we also highlight that not all service types require or benefit from the protection of the large 500 m exclusion zones, which also limits the spectrum utilization.

A two-tier spectrum allocation approach is proposed, where each network is assigned two separate spectrum parts, using the bandwidth part functionality of 5G. One large allocation for best effort and high throughput traffic, and one smaller allocation reserved exclusively for critical traffic. The exclusive spectrum portion is never reused within a 1 km range, while best effort spectrum can be reused for network

separations of 100-1000 m. Compared to the reference scenario where all networks are given exclusive spectrum with a 1 km reuse distance, the proposed method yields 2-5 times higher network capacity while still protecting the critical traffic. We recommend that the proposed model be considered to allow dense deployments of 5G private networks. Potentially stimulated with a layered spectrum pricing model that encourages the use of larger shared spectrum versus exclusive access to protected spectrum.

## ACKNOWLEDGMENT

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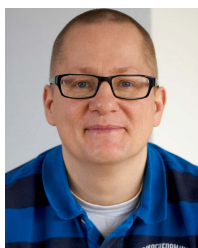
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