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 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, 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-serve 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. For example, in Denmark the recommended exclusion zone is 500 m, defined from the service boundary of the private network [6]. In practice, this means that only a very low density of private networks can be supported given 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 (C-BRBS) band, which stretches between the 3550–3700 MHz. However, the C-BRBS 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-serve 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 license 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 500 m 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 dBm/m²/5MHz 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 km² 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 km².

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

III. SYSTEM MODEL

In this study we consider dense deployments (≤500 m regulated exclusion zone), ex. in sub-urban and urban areas, and assume micro-grade network equipment with a maximum transmit power of 30 dBm. To study a hostile interference environment, we place 9 identically configured private net-
works in a square grid as illustrated in Fig. 1. Each network consists of two base stations (gNBs) separated by 50 m, each with a circular service area with radius of 50 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 5G NR centred at 3.5 GHz and configured to the same overlapping 90 MHz bandwidth. The square grid of 9 networks are 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.

![Network separation](image)

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

### A. SQUARE GRID LAYOUT - OUTDOOR DEPLOYMENT

In the outdoor deployment scenario, each of the 9 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 m, each with a 50 m service area radius, meaning there is a maximum of 75 m from the network center to the edge of the service area. Placing the networks with a network separation of $X m$ is achieved by fixing the distance between the networks centre as $75 m + X m + 75 m$. 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 $X m$. The network separation ranges from negative 100 m up to 1000 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 indoor, and there is 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 m × 125 m buildings as depicted in Fig. 2. The external wall penetration loss is set conservatively to not overestimate the performance, at 10 dB per wall [17], [18]. The considered distances between the external building walls ranges from "0m" and up to 350m. As the size of the building just extends to furthest point of 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 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 needs 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 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 model 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 decod-
A summary of the key simulation assumptions are shown in Table 1. Both UE and base station have two antennas, but 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 subcarrier spacing (SCS) with 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 \( P_0 = -90 \text{ dBm} \) 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].

### 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 antenna Gain                        | 30 dBm                                          |
| gNBs per network                        | 9 dBi                                            |
| UE distribution                         | 2                                               |
| UE receiver                             | Uniformly distributed, 5 UEs per cell           |
| Network gNB-gNB separation              | MMSE IRC receiver                               |
| gNB service radius                      | 50 m                                            |
| Frame format                            | 50 m                                            |
| Traffic model                           | DDDSU                                           |
| Channel model outdoor                   | Full buffer                                     |
| Channel model indoor                    | 3D Urban-micro                                  |
| External wall penetration loss          | modified COST 231 multi-wall model              |
| UL power control                        | 10 dB                                           |
| Scheduling (UL & DL)                    | \( P_0 = -90 \text{ dBm}, \alpha = 1 \)        |
| Link adaptation                         | Proportional fair (time and frequency)          |
| Mobility                                | Max Scheduled Users = 5/TTI                     |
| Mobility                                | Inner and outer loop, 10% BLER target           |
| Mobility                                | Async HARQ, incremental redundancy              |
| Mobility                                | Static, fast-fading speed: 3 km/h               |

### V. PERFORMANCE RESULTS

Fig. 3 represents the empirical CDF of average simulated user throughput for four different network separation 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 lower percentage of users in a low throughput condition.

![Figure 3: CDF of user throughput for X[m] network separation (Outdoor).](image)

In Fig. 4 the guaranteed user throughput for 50, 90, 95, and 99% of users are shown. The throughput performance is

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considered to be converging when further increase in network separation only adds minor or no increase in throughput performance. The downlink performance converges at different distances of the network separation, with 50% converged already at 0 m and 99% converging at approximately 800 m. If the regulated exclusion zone 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 400 m. The uplink performance results in Fig. 5 shows a different sensitivity to interference 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 more likely to have much higher penetration loss in external walls, leading to even better isolation of the networks.

The outdoor scenario where all 9 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. 300 m for 95% of users (Fig. 4). To reduce the interference
in dense deployments, the available spectrum can be divided such that each network gets their 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 among securing high quality access with high reliability and basic capacity for best effort services.

VI. TWO-TIER BANDWIDTH ALLOCATION SCHEME

We consider next 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 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 where 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 handling 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 9 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). 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. From fig. 4, it can be observed that the throughput is nearly converged for 90% service availability already at 100 m network separation. 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 plot 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 is required to satisfy reuse distance above 1000 m for critical allocation to all 9 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 networks 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...
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