# Deployment of a Cellular Network in the TVWS: A Case Study in a Challenging Environment

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## ABSTRACT

In this paper we analyze the potential of TV whitespaces for secondary cellular use. We study the situation where a single cellular operator improves the performance of its network by upgrading its existing cell-sites to opportunistically and cost-efficiently utilize secondary spectrum resources. We determine the available capacity for such networks under interference-margin constraint rules and use terrain-based propagation models to retrieve realistic coverage predictions. We report on our findings from a particularly challenging environment in Western Germany, where border and geographical conditions impose significant limitations on the efficient use of whitespaces. However, our methodology and use-case scenarios are generic, and the specific geographical study can be seen as a blend of worst-case approximation of spectrum diversity and best-case scenario for coexistence between secondary systems.

## Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

## General Terms

Design, Performance

## Keywords

TVWS, Network Planning, Spectrum Regulations, Coexistence

## 1. INTRODUCTION

TV whitespaces (TVWS) have received renewed attention after the 2010 FCC-ruling on the opening of these bands for secondary systems [5]. The use of TVWS for mobile communications holds a promise to provide substantial extra capacity for different secondary systems, and thus is an interesting concept not only academically but also commercially. So far most of the works on TVWS have focused on studying single (ad hoc) secondary transceiver pairs or WiFi-type deployments to gauge various problems such as sensing, interference and coexistence. Studies on the capacity limitations of the TVWS on the other hand have, until recently, considered mostly general systems and made only coarse-grained assumptions on the secondary usage scenarios. The ground breaking work from the capacity point of view was done for the TVWS in the USA by Harrison et al. [7] and a similar exercise was carried out later for selected European countries by van den Beek et al. [2].

We argue that in order to assess the existing capacity opportunities and the economical viability of secondary operations, the secondary user model needs to be reasonably well defined. The spatial structure of secondary networks and the type of operations determine how efficiently underutilized spectrum can be exploited. In this study we assume that the secondary user is a single cellular operator, which is reusing its existing cell-sites also for secondary transceivers (base stations). We are particularly interested in how the secondary's existing spatial structure, the distribution of secondary users and the frequency planning potentially limit exploitation capabilities. As far as we are aware this is the first detailed study of this kind for TVWS.

The assignment of secondary spectrum resources to each of the operator's base stations is particularly complex in this scenario. While traditional cellular network planning is conducted to optimize for capacity for operations in dedicated mobile bands, in secondary operations the protection of the existing TV network also needs to be accounted for. Furthermore, cell sizes and locations of base stations are chosen for a frequency range with different propagation characteristics, which limits the options for secondary exploitation. A core research question we address here is to what extend the configuration of the network can be adjusted for different optimization objectives such as coverage or throughput.

To test our methodology, we have chosen a district in the most Western part of Germany commonly known as the Southern Rhineland. This Central European region shares borders with The Netherlands, Belgium and other German federal states, each of them sovereign in its TV broadcast planning and targeting best coverage for its citizens. The configuration of TV transmitters and transmit powers shows a significant amount of overlap and overprovising. Of the approximately 4.4 million people in the Southern Rhineland, most live in the central part on the river Rhine in the city of Cologne. The mountainous rural areas in the South West are only sparsely populated. Propagation characteristics in the region are dominated by the mountains in the South and

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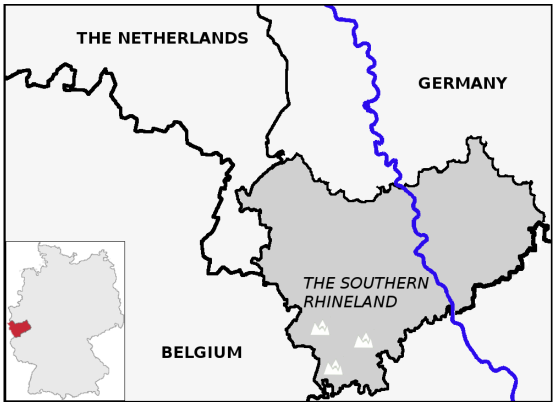


**Figure 1: The Southern Rhineland.**

East and flat terrain in the central region. Given all these aspects it is suitable to describe this region as "challenging" for the optimized construction of a wide-area network.

This paper is organized as follows: Section 2 is dedicated to the question of how much TVWS may be made available in a region subject to the described technical and regulatory difficulties. We incorporate the technical constraints of primary TV receivers and discuss different options for the regulatory implementation of a proposed whitespace ruling. We assume a fixed interference margin for the primary receivers that will allow the secondary transceivers to run at high powers if they are located at a sufficient distance. The possibilities for operating a cellular-type secondary network within this environment are studied in Section 3. Finally, conclusions on the feasibility of such secondary operations are drawn in Section 4.

# 2. SPECTRUM RESOURCES FOR SECONDARY OPERATIONS

The locations of the TV broadcasting towers in the Southern Rhineland are optimized for reliable and extensive coverage. The individual allotment of spectrum and the choice of transmit powers for different channels targets to avoid intra-network and cross-country interference. This results in a broadcasting network that exploits its spectrum resources inefficiently, and at the same time shows large local variations in spectrum use. Setting up a secondary network to coexist with the existing installation is therefore highly complex. In the following we will first investigate how much spectrum is left for a secondary use. Since there is no German or European ruling in TVWS, yet, we assume a protection rule based on the current draft of the European Communications Office [3].

## 2.1 Coverage edge calculation

The specific combination of modulation scheme and code rate of the multiplexed DVB-T signal determines the minimum SINR value required for a TV receiver at the coverage edge. For the DVB-T system in Europe, a BER of $2 \times 10^{-4}$ after Viterbi decoding is defined as a general planning target [4], mapping to a SINR between 11 and 19 dB.

In order to estimate the signal attenuation at the coverage edge, power prediction needs to be conducted. Two methods have evolved to be de-facto standards for TV network planning in this context: the ITU-R P.1546-3 [10] for general-purpose planning task and the Longley-Rice Irregular Terrain Model [8] for terrain-aware propagation modeling. We use the latter in this paper due to the diversity of the studied region [2].

## 2.2 Protection of the TV system against secondary interference

The current trend in Europe, particularly in the Spectrum Engineering Working Group 43 (SE43), tends towards the implementation of a flexible interference margin for transmissions of CR devices [3]. Under this regime, secondary devices may operate at high power levels as long as the received additional aggregate interference at any TV receiver does not worsen the TV reception beyond a particular threshold interference margin ($IM$), e.g. 3 dB.

We adopt the coverage planning methodology used by regulators and TV network operators for the common scenario of a 64-QAM TV transmitter and a receiver-side fixed rooftop antenna installation. In this case the DVB-T standard [4] states the minimum decodable SINR in a Ricean fading channel to be $SNR_{min} = 14.7\,\text{dB}$. Given thermal noise of $N \approx -105.2\,\text{dBm}$, an antenna gain $AG$ of 10 dBi [9], and an additional loss margin $L = 10\,\text{dB}$ (e.g. due to cable losses), it must hold that for every point in the protected contour of the system it is

$$SNR = P_{TX} + AG - PL - L - N - IM \geq SNR_{min}, \quad (1)$$

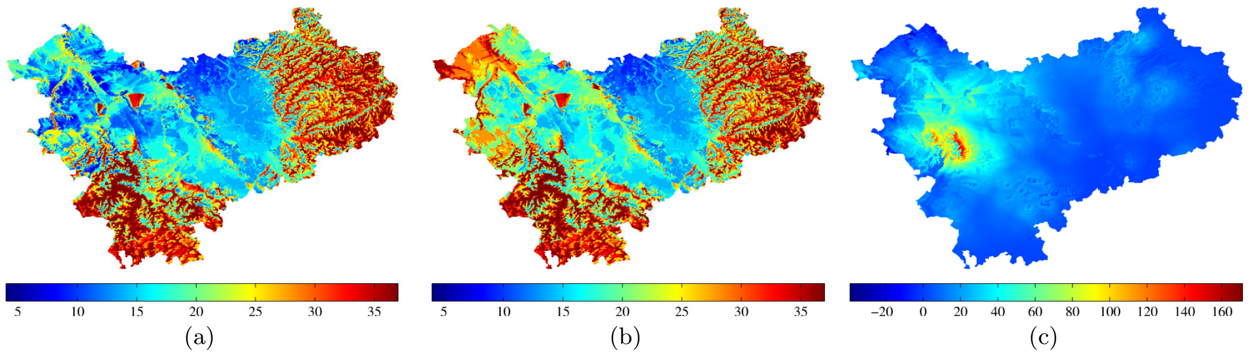
where $P_{TX}$ is the equivalent isotropically radiated power (EIRP) of the TV transmitter and $PL$ is the pathloss for the specific environment as predicted by the propagation model. To account for receiver filter imperfections, the first adjacent channels below and above the received channel need to be protected with a 40 dB offset [3]. Given the configuration of this example, the protection contour for $IM = 3\,\text{dB}$ will be defined as the points at which

$$P_{RX} = P_{TX} - PL = -87.5\,\text{dBm}. \quad (2)$$

## 2.3 Number of accessible channels for cellular operations

We base our study on a database of TV transmitter locations and transmission parameters provided by the German Federal Network Agency [6]. Altogether 72 transmitter locations are modeled with a total of 231 tower-channel combinations. We limit the potential secondary operations to the UHF-IV and and parts of the UHF-V bands from 470 MHz to 800 MHz. The upper frequency range of the UHF-V band from 800 MHz to 892 MHz has been recently assigned to mobile broadband services and is hence not considered for secondary usage. The European DVB-T system employs an 8 MHz channel matrix.

Figure 2(a) shows a color-coded map of the studied area depicting for each location the number of channels not protected by the secondary usage policy. A large variation in channel availability exists with as little as 5 unprotected channels in the North and up to 37 channels in the South West. We found this result to originate from two distinct facts: The Southern area is shielded from out-of-region TV transmission by mountains. The flat central area on the contrary is highly overprovisioned, with the same set of TV stations visible on up to 4 physical channels at the same



(a) (b) (c)

**Figure 2: Channel availability as predicted by the Longley-Rice propagation model. Figure 2(a) shows the number of unprotected channels if a generic protection rule is applied. In Figure 2(b) channels are only protected within the respective home countries of the TV stations they carry. The increase of theoretically achievable throughput (in percentages) for loosened ruling is shown in Figure 2(c).**

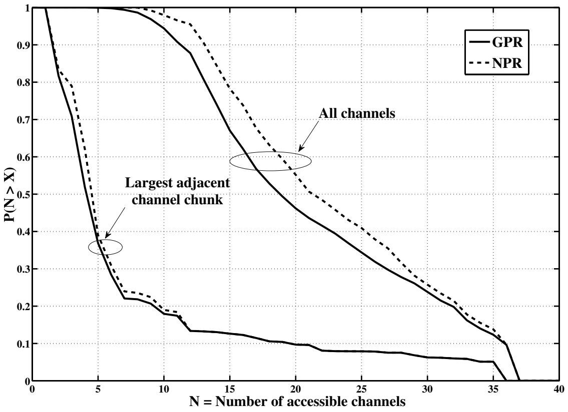


**Figure 3: Complementary cumulative distribution function of point-local number of unprotected channels.**

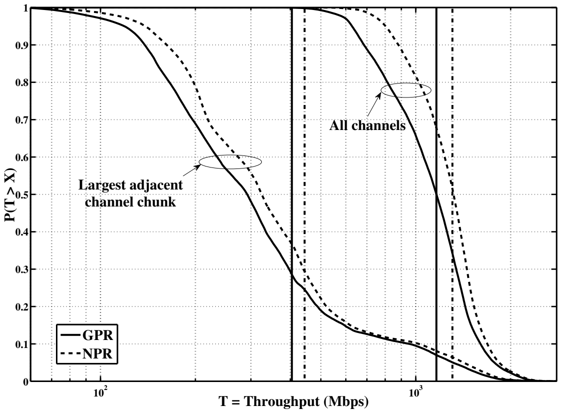


**Figure 4: Complementary cumulative distribution function of point-local theoretical throughput. Vertical lines show respective mean values.**

time. A local TV station network with regional division of their newscast worsens this situation.

The border area is seriously disadvantaged compared to inland regions because of foreign TV signals. For this reason we will also consider a loosened protection rule, denoted as *No-Neighbour Protection Rule (NPR)*, that protects channels only within their respective home countries. Figure 2(b) shows that regions in the West benefit significantly from this liberalization. We found that whereby in 49.36% of the studied region up to 19 channels are encountered unprotected, this ratio is raised to 59.36% if the neighbor protection lifted, see Figure 3.

## 2.4 Single secondary transmitter throughput

The application of an interference margin as described in Section 2.2 causes the achievable throughput to implicitly depend on the minimum distance to the respective protection contour. Initially we consider only a single transmitter, randomly located within the studied region and exploiting all of the unprotected channels with maximum allowable power. To account for shadowing and fading effects in the interference path we retrieve the 5th percentile of the pathloss coefficient. Figure 4 shows the complementary cumulative distribution function (CCDF) of the theoretical maximum of achievable throughput if the secondary link is modeled as lossless. This theoretical boundary is derived for an AWGN channel through application of the Shannon-Hartley Theorem, secondary coding imperfections are neglected as in [7]. On average, each accessible channel provides for 53.2 Mbps of gross throughput (1163 Mbps in total for all local channels) and this metric can be improved by 4.4% if the neighbor protection is removed. If only the largest continuous channel chunk is accessed by the transmitter, the capacity lowers by roughly 65% in both cases.

The reader should note that a secondary transmitter at the border is subject to a significantly higher noise floor in channels that are declared accessible by the NPR ruling. In the worst case, the additional noise will even worsen the average per-channel performance of the transmitter compared to the protected case. As depicted in Figure 2(c), transmitters that are not directly at the border as a consequence benefit most from the ruling.

# 3. SPECTRUM ALLOCATION IN A SECONDARY CELLULAR NETWORK

In our scenario, the network operator wants to extend its existing cellular services by using the available TVWS. Since the cellular network is already deployed, we consider the number and locations of the base stations to be fixed and the coverage area of each cell is predetermined by the current primary usage. For simplicity but without losing generality we assume that the operator has exclusive access to all TVWS spectrum resources.

## 3.1 System model

We use a database that comprises the exact coordinates of all base stations of an existing large network operator which offers cellular voice and data services to mobile users in the 900 MHz bands in the respective region. This provides for an accurate and realistic deployment model for TVWS base stations. We approximate the coverage area of each base station by Voronoi decomposition [11]. To ensure a robust handover between adjacent cells for mobile whitespace devices, the cell edge is furthermore increased by 70 meters. In order to keep the system model tractable, we assume omnidirectional antennas and consider only downlink communications.

In order to operate a base station in a specific TV channel, the minimum power requirements need to be known. These depend primarily on the residual power of the DVB-T system and the target SINR at the cell edge $SINR_{target}$ for which the network coverage is dimensioned. Thus we have

$$\begin{aligned} P_{min,i,c} &= 10\log_{10}(I_{max,c,DVB}\ [mW] + 3.2\times 10^{-11}) \\ &\quad + PL_{BS\rightarrow CE} + SINR_{target} \end{aligned}$$

as the minimum power required by the base station $i$ to serve its users on channel $c$, whereby $PL_{BS\rightarrow CE}$ is the pathloss from the base station to the cell edge and $I_{max,c,DVB}$ is the maximum interference from the DVB-T system. A base station is only eligible to use a particular channel if

$$P_{min,i,c} - PL_{BS\rightarrow p} < -105.2\ [dB]\ \forall\ p \in P_c$$

with $p$ being any point within the protection contour $P_c$ of a channel.

## 3.2 Allocation strategy for multiple secondary base stations

From the set of all possible assignment of channels to base stations $\Psi$, the network operator will choose a preferred and allowed constellation $\psi^* \in \Psi$ that maximizes an economic or technical objectives while protecting the primary system.

We partition the allocation problem and define $\psi_c$ as a binary vector of $n$ elements, with $n$ being the number of base stations, for which

$$\begin{aligned} \psi_c &= (\psi_{c,i} \in \{0,1\} : \psi_{c,i} = 1 \text{ if BS } i \\ &\qquad \text{uses channel } c, i \in [1,n]). \end{aligned}$$

From the set of all permutations of active base stations we allow only those constellations for which

$$\sum_i P_{min,i,c} \times PL_{BS\rightarrow p} \times \psi_{c,i} \leq 3.2\times 10^{-11}[mW]\ \forall\ p \in P_c,$$

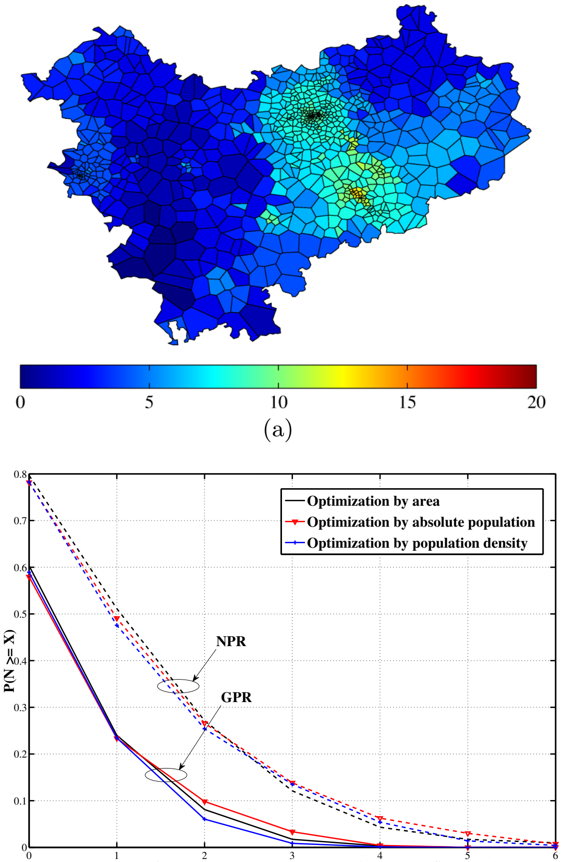
i.e. the aggregate interference constraint to the primary is fulfilled. In order to minimize co-channel interference, we specify an $n \times n$ adjacency matrix $A$ with entries $a_{i,j} = 1$ if base station $i$ and $j$ share an edge of their respective Voronoi cells, $a_{i,j} = 0$ otherwise. The optimization problem must adhere to the constraint $A\psi \leq \mathbb{I}$, where $\mathbb{I}$ is the unit matrix. We hereby ensure that two adjacent base stations will never use the same channel, an assumption equivalent to a network design with a frequency reuse factor of 3.

From the set of constellations that fulfill both constraints $\Psi_c^A$, we find

$$\psi_c^* = \underset{\psi_c \in \Psi_c^A}{\operatorname{argmax}} \sum_i \psi_{c,i} o_{c,i}. \qquad (3)$$

$O_c = (o_i \in \mathbb{R} : o_i \geq 0, i \in [1,n])$ is the objective vector representing the benefit the operator may gain from activating channel $c$ on base station $i$.

## 3.3 Simulation results



(a)

(b)

**Figure 5: Per-base station channel accessibility for a target SINR of 23dB. The regional distribution in Figure 5(a) depicts GPR ruling. Figure 5(b) gives the respective CCDFs.**

For our analysis we have implemented a custom MATLAB toolchain to calculate spectrum exploitability. Splat! [1], an RF Path Analysis Application, was used for field strength

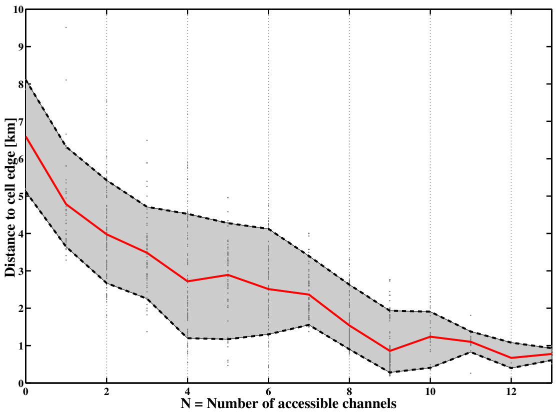
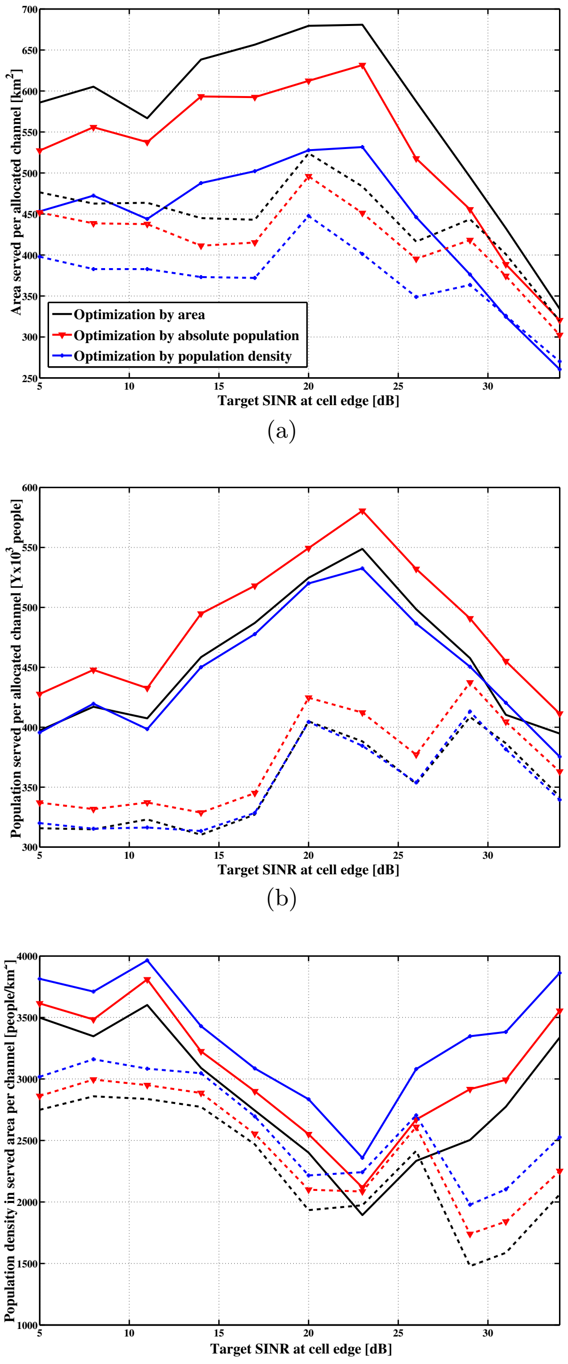


**Figure 6: Relationship between the number of accessible channels in a cell vs. the distance from base station to the cell coverage edge. Solid line represents the median, gray area is delimited by 10th and 90th percentile.**

calculations. For all local 925 base stations we first derived the maximum transmit power assuming the 5th percentile of the pathloss to the nearest point in the protection contour. The required transmit power for a particular target SINR was calculated for the 95th percentile of the pathloss to the extended cell edge. This step removes those base stations for which the required transmit power exceeds the allowed power. In order to find the critical protected point at which the aggregate interference from the remaining base stations was highest, we conducted an exhaustive search. Through heuristic iteration over the possible search space, a objective-maximizing constellation was found that fulfills the neighborhood constraint while keeping the induced power at the critical point below the interference threshold.

In Figure 5 we show how many channels a single base station may use if its target SINR is 23 dB and it respects the power constraints described in Section 3.1. The results indicate maximum channel accessibility in the central region. This is surprising given that our previous findings on channel availability in Figure 2 implied that other areas feature more accessible channels. A comparison between the size of the coverage area of a base stations and the number of accessible channels, depicted in Figure 6, shows that microcells that are predominantly found in the central region can better exploit the available channels due to their lower power requirements. Oppositely, the likelihood of interfering with TV reception significantly increases for large secondary coverage areas and lowers their accessibility.



(a)

(b)

(c)

**Figure 7: Results of optimization schemes for different performance measures. Solid lines denote the GPR rule set, dashed lines show NPR ruling results.**

In the following, we will discuss methods to efficiently exploit the TVWS by the secondary network given different cell sizes and large variations in the population served in each cell. These results are indicative for the economical and technical viability of a secondary cellular deployment. A first intuitive approach to the optimization problem is to define the optimization vector such as to maximize the per-channel coverage area. As shown in Figure 7(a), this allocation strategy produces stable average channel coverage area sizes up to a target SINR of 23 dB. By further increasing the SINR requirements (and hereby implicitly also the achievable per-cell/per-user throughput), the macrocell base stations fail to meet the maximum power constraint and large areas remain unserved. This observation is also reflected in Figure 7(b) for the absolute population served and Figure 7(c) for the population density of the respective served area. Increasing the target SINR results in a substitution effect of single macro- vs. multiple microcells that is limited by the absolute number of microcells.

A second approach is to instead maximize for the absolute population served by each channel. Figure 7(b) shows that on average 30,000 people more are covered per channel if the optimization is conducted in this way. Beneficiary to this assignment strategy are primarily the central microcells with high population densities. Rural areas, represented by large macrocells, remain unserved as indicated in Figure 7(a). We can consider this strategy to be highly biased towards small cells-sites because of the underlying negative correlation between cell sizes and population density. A modified optimization scheme that maximizes for the population density in the served area further worsens this effect.

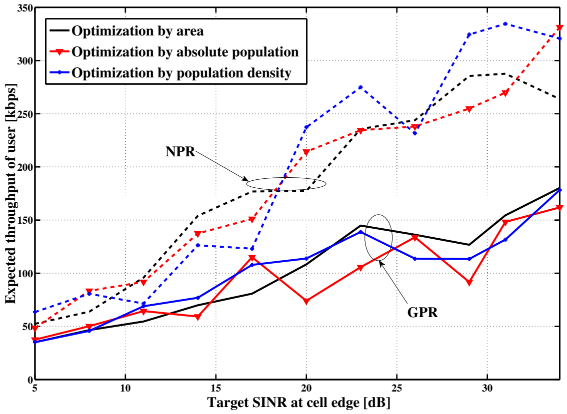


**Figure 8: Expected maximum available throughput per user. Capacity is equally shared between cell users, sharing protocol overhead and intra-cell interference are neglected.**

A conclusion we can draw from the comparison of these schemes is that the cellular network structure, optimized for utilizing licensed spectrum resources, affects the exploitation capabilities of secondary spectrum more significantly than expected. The estimation of per-user maximum achievable throughput furthermore reveals that no classical optimization scheme is superior in exploiting the secondary spectrum, see Figure 8, but all provide increasing throughputs for those users that are assigned secondary spectrum.

# 4. CONCLUSIONS

In this paper we have studied the prospects of exploiting unused spectrum capacities in the TVWS for extending the spectrum resources of an existing cellular network. The developed methodology has been assessed in a Central European region by using exact terrain models and base station location data from a real cellular deployment. We have estimated the achievable capacity with respect to two potential implementations of regulatory ruling in this challenging environment and studied effects of different network planning goals.

The results show that the spatial structure of the cellular network affects more significantly its secondary spectrum exploitation capabilities than expected. The predominance of macrocells in rural areas and microcells in urban areas constitutes a serious limitation to the optimal assignment of spectrum resources to cell-sites. We discovered that neither the local count on channel availability nor the raw channel capacity is a reliable indicator for achievable performance in a secondary cellular network usage scenario.

Another important observation is that there seems to exist an optimum target SINR at cell edges to exploit the spectrum capacities for a given optimization objective most efficiently. This SINR coincidences with the accessibility of channels by large macrocell installations and is not aligned with other measures such as the maximum per-user throughput.

An auxiliary result from our choice of studied region is that the achievable capacity in a country's border area can be significantly improved if TV channels are required to be protected only within their respective countries.

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