On the Performance of Dynamic Spectrum Access based on Spectrum Occupancy Statistics

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Abstract

At present multiband wireless devices are able to select their working frequency only to a limited extend due to the strict, current spectrum regulation. Dynamic spectrum access is a promising approach that might solve this inefficiency. In this paper we focus on spectrum sensing, one of the main tasks involved. First, we compare three strategies to efficiently sense the current spectrum based on the spectrum occupancy information statistics. Contrary to simulation-based studies, we evaluate the performance of those strategies on real spectrum occupancy data gathered during an extensive measurement campaign. We show that the usage of historical information considerably improves the spectrum sensing process. We also show that the modelling of the periodic behaviour of the licensed signals leads to negligible performance enhancements because only very few periods shorter than several minutes can be found within 20 MHz-6 GHz. Second, we unveil the fundamental tradeoff between the required bandwidth for the transmission and the total bandwidth that has to be sensed in order to guarantee that the required bandwidth is available. All the results are provided in terms of outage probability which can be viewed as an approximation of the packet loss rate.

I. Introduction

The flexibility and adaptiveness of wireless devices has been significantly improved during the recent years. Meanwhile the involved system complexity increased considerably. In the Cognitive Radio paradigm [1], [2], devices are aware of their surroundings and capable of learning in order to manage this system complexity. The working frequency and the used bandwidth are two of the main working parameters that cognitive radios could dynamically optimize in order to adapt to the environment variations [3]. These proposals have also been motivated by several measurement results (e.g., [4]–[8]) that showed the inefficiency of the current mostly static spectrum regulations. All these measurement campaigns have found significant amount of unused spectrum (e.g., 80 % in GSM bands in the case of normal usage [8]). Such vacancies were found despite of the fact that most of the spectrum is licensed. This has led many authors to argue that the current spectrum regulation is highly suboptimal. Advanced techniques for Dynamic Spectrum Access (DSA) attempt to exploit the free spectrum by extending the idea of unlicensed access [9]. In this context, some users referred to as secondary users look for unused spectrum bands and opportunistically transmit if no licensed signal has been sensed. A licensed signal is sometimes also referred to as primary user signal [3].

The search for free spectrum is based on various sensing techniques, see, for instance, [10] and the references therein. Often energy detection is applied [11], but more powerful techniques can be applied if further statistical information on the licensed signals is available or can be estimated [12]. Independently of the sensing technique, the device has to select a specific subband for sensing among a pre-determined set. The larger the covered bandwidth, the higher the energy consumption of the sensing system [13]. Therefore, systems that sense multiple Gigahertz bandwidth are realistic for spectrum sensing infrastructure but less reasonable for mobile devices. In order to reduce the implementation complexity several techniques have been recently proposed. For instance, the authors propose in [14] to delay the next sensing action if a channel has been sensed as occupied. This adaptive time resolution of spectrum sensing lowers the spectrum, that has been scanned occupied, and thus improves the efficiency of the system. In addition to the duty cycle, several researchers showed the benefit of exploiting deterministic behaviour and periodicities in spectrum occupancy data for DSA (see e.g., [15]–[17]). However, the performance of these methods has not been evaluated with measured data and it is not clear if such theoretical gains can be achieved in practice.

In this paper, we present a detailed comparison of adaptive spectrum sensing techniques and their evaluation based on measurement traces taken from our extensive spectrum occupancy study [18]. In the first step, we use the probability that the measured band will be free as performance metric. Hence, selecting the bands with the highest probability will enhance the sensing efficiency most. We also consider algorithms that exploit the periodicities of primary user signals. Our comparison shows that the number and the strength of these periodicities are too small to yield non-negligible performance gains. Second, we extend the analysis to determine the minimum amount of bandwidth to sense in order to find an unoccupied band which fulfills the minimum transmission requirements. We apply the outage probability p_{outage} as appropriate performance metric in the new context of adaptive sensing techniques and enable the consideration of application requirements in the physical layer sensing process in a cross-layer fashion. The results based on our real measurement data show that historical information can also be used to significantly improve the decision on the amount of spectrum that has to be sensed.

The remainder of this paper is structured as follows. In Section II we shortly introduce our measurement setup. In Section III we present three methods how historical information can be used to improve spectrum sensing in a smart way and compare those based on our measurement data. We extend the approach towards the tradeoff between the sensed bandwidth and p_{outage} in Section IV and include further evaluation, again, using our measurement results. Finally, we conclude the paper in Section V.

II. Measurement setup

The analysis presented in this paper is based on real data that was taken during an extensive spectrum occupancy measurement campaign [18]. The equipment was located on the roof of the International School Maastricht, Maastricht, Netherlands. The measurement setup is based on an Agilent E4440A high performance spectrum

TABLE I

SPECTRUM ANALYSER CONFIGURATION USED THROUGHOUT THE MEASUREMENTS [18].

Center frequency	Subband 1: 770 MHz
	Subband 2: 2250 MHz
	Subband 3: 3750 MHz
	Subband 4: 5250 MHz
Frequency span	1500 MHz
Resolution bandwidth	200 kHz
Number of measurement points	8192
Sweep time	1 s
Measurement duration	About 7 days per subband
Detector type	Average detector
Preamplifier	Up to 3 GHz: 28 dB gain

analyser, which is remotely controlled via Ethernet by a standard laptop. We used two discone antennas of different size and one radom antenna to cover the frequency range between 20 MHz and 6 GHz. All antennas are vertically polarized, are omnidirectional in the horizontal plane and have small amount of directivity in the vertical plane. The settings of the spectrum analyser are detailed in Table I. The resolution bandwidth of 200 kHz is a compromise between the frequency resolution and the maximum span which can be measured in one sweep. As the goal of our campaign was to investigate the spectrum occupancy behaviour over longer time periods, we selected a lower frequency resolution in order to limit the required number of separate measurements. The results presented here are limited to the first two subbands because most real-life systems work in the frequency range between 20 MHz and 3 GHz. A detailed description of the measurement setup and further measurement results were reported in [18].

III. SMART SPECTRUM SENSING BASED ON HISTORICAL INFORMATION

In this section we shall evaluate how historical information can enhance the efficiency of spectrum sensing. First, we concentrate on the problem of which frequency band should be sensed. Later, we extend the investigation to the amount of sensed spectrum and its impact on the probability to find as much free bandwidth as requested by the application.

A. Determination of the probability of finding free channels

The primary goal of the smart spectrum sensing is to reduce the amount of spectrum to be sensed. Spectrum which was busy at the previous sweep, i.e., 1 sec before, is very likely busy at present [13]. Therefore, a simple strategy for adaptive spectrum sensing consists of identifying those channels with the highest probability of being free. In this paper we compare three different methods to the reference case that senses at random and does not rely on any historical information. All three are based on a set of probabilities that describe a binary occupancy state machine for each single channel but use different historical information. We interpreted all measurement results taken by the spectrum analyser at a single frequency index as a time series. The whole measurement trace of more than 330000 consecutive samples over ≈7 days was used to compute the occupancy probabilities for each frequency bin.

We determined the binary state Ω (*free* or *occupied*) of each sample using energy detection. The occupancy decision threshold is set to $\gamma =$ -107 dBm as it has been specified by the IEEE 802.22 standardisation group [19] for the detection of wireless microphones, which also use 200 kHz channels. Denote the received power at time instance t in channel i as $P_{rx,\,t,\,i}$. The channel is said to be occupied, i.e., $\Omega_{t,\,i} = 1$ if $P_{rx,\,t,\,i} \geq \gamma$ and free otherwise ($\Omega_{t,\,i} = 0$). Furthermore, denote L_i as the overall number of samples taken at channel i and DC_i as the duty cycle, i.e., the percentage of samples representing an occupied channel:

$$\Omega_{t,\,i} = \begin{cases} 0 & \text{if } P_{rx,\,t,\,i} < \gamma \\ 1 & \text{if } P_{rx,\,t,\,i} \geq \gamma \end{cases},$$

$$DC_i = \frac{\sum_{t=1}^{L_i} \Omega_{t,\,i}}{L_i}. \tag{1}$$

1) Reference case: No available historical information to decide if the channel will be free or not: The reference technique does not use any historical information and thus does not preferentially select channels with low duty cycle. Instead, it tests the channels randomly. The probability of selecting a free channel is $p_{ref}(free) = \mathbb{E}[1 - DC_i]$, where $p_{ref}(free)$ is the probability that the channel sensed by the reference method will be free, DC_i is the duty cycle in channel i and $\mathbb{E}[1 - DC_i]$ is the expectation of a channel to being free, taken over all frequencies.

2) Duty cycle based method: The duty cycle based method chooses the channel with lowest duty cycle. The probability of selecting a free channel can be expressed as: $p_{DC}(free) = 1 - \min(DC_i)$. The duty cycle was used in similar context in [14].

3) First order Markov chain: The inter-sample time of our measurement traces is about 1.8 sec, which consists of the configured sweep time of 1 sec plus further delay for instrument realignments and the data transfer from the spectrum analyser to the laptop. We assume that the durations of most of the sessions are longer than such a short period. Therefore, our spectrum measurements are correlated over time. The probability that the channel state switches between two states (*free* to *occupied* or vice-versa) will be much smaller than the probability to stay in the current state. We consider in this paper the state of the previous sample only. Such a system can be represented using a first order Markov chain. Higher order Markov chains or other models may capture a more complete temporal description of the correlation but we limit our analysis here to the first order case.

We determine the probability of transition $\rho = p_{Markov}(\Omega_t = 1 | \Omega_{t-1} = 0)$ from state *free* at time lag $t-1$ to state *occupied* at time lag t from our measurement traces. Afterwards, we combine it with the duty cycle information to calculate the probability of transition from state *free* to state *occupied*: $p_{Markov}(\Omega_t = 0 | \Omega_{t-1} = 1) = \rho \cdot (1 - DC)/DC$. The probability $p_{Markov}(\Omega_t = 0, t | t-1, i)$ of a channel i to be free at the time lag t can then be expressed as:

$$p_{Markov}(\Omega_t = 0, t | t-1, i) = \begin{cases} 1 - \rho_i & \text{if } \Omega_{t-1,i} = 0 \\ \frac{\rho_i \cdot (1 - DC_i)}{DC_i} & \text{if } \Omega_{t-1,i} = 1. \end{cases}$$

We evaluate $p_{Markov}(\Omega_t = 0, t|t-1, i)$ based on our measurements by selecting the best channel at time t which maximizes $p_{Markov}(\Omega_t = 0, t|t-1, i)$ and averaging this probability over $L = 10000$ samples (≈ first five hours of our measurement traces); i.e., $p_{Markov}(free) = \mathbb{E}_t[\max_i(p_{Markov}(\Omega_t = 0, t|t-1, i))]$.

A Markov-chain based approach to DSA was also used in [17] for the special case of DSA in WLAN channels.

4) Method exploiting periodicity: Exploiting the periodicities of the primary user signals in order to enhance DSA systems has been proposed in [15]–[17]. However, it is not clear if such improvement is also attained with real data. We detected the periodicities in our measurement data using Fourier transform. The Fourier coefficients for each frequency bin indicates the strength of the respective periodicities [20]. The most dominant periodicities are usually rather long, e.g., 24 hours and express the dependency of the spectrum occupancy on the time of the day. We actually found only few periods that were shorter than five minutes. Longer periods are not accurate on a per sample level but describe more general trends and cannot be exploited for adaptive sensing. For the lower limit our rather low time resolution of about 1.8 sec inter-sample time prevented to detect periodicities such as the television blanking interval. However, these periodicities are not of interest in our approach as we expect that it is significantly more complex to exploit such very short periods in commercial products because of the high requirements on synchronization and sensing speed.

Although we found short periodicities ≤ 5 min in only few bands, we also evaluated the performance of adaptive sensing based on such historical information. It is similar to the Markov-case except that we consider a time shift of τ sample durations instead of using the knowledge of the previous sample. We determine τ as the period below five minutes with the highest Fourier coefficient. If such a period is not present in the considered subset of the 15 strongest Fourier coefficients for some frequency bins, we base our probability calculation for these frequencies only on the duty cycle. Later on, we average $p_{Period}(free)$ also over $L = 10000$ time lags as we did for the Markov chain approach.

B. *Results*

The four aforementioned techniques determine the probability that a channel of 200 kHz bandwidth will be free at the next time lag. In order to support bandwidth demanding services such as video streaming, we also evaluate the probability that a bandwidth larger than 200 kHz will be sensed free. We differentiate two cases. In the first case, the bandwidth does not have to be consecutive. If a single secondary user accesses the free spectrum, he should be capable to null some frequencies within the bandwidth he is transmitting that are used by the primary users. This can be done by using wideband multi-carrier technique [21]. In the context of a centralised system with multiple secondary users, each consecutive free portion of spectrum can be allocated to a single secondary user depending on his throughput requirements. The second case requires that the free bandwidth is consecutively usable in a secondary fashion and single- and multi-carrier systems could benefit from it. In order to make our analysis more concrete and quantitative, we evaluate the four methods to efficiently sense specific bands or sets of specific bands.

1) Analysis of the UMTS uplink band: As a first example we investigate the UMTS uplink band [22], which is allocated from 1899.9 MHz to 1979.7 MHz in the Netherlands. Figure 1 shows two groups of curves, one for the case of non-consecutive and one for the case of consecutive bandwidth. We first evaluate the probability to find up to 40 MHz free bandwidth in the case exactly the same amount of bandwidth is sensed. If the adaptive sensing applies one of the described four methods, this corresponds to the case where all sensed channels are free. Clearly, sensing further channels increases the probability of finding free bands as we report in section IV.

The graphs for the reference method (i.e. without any historical information) start at the value for a single channel, which is one minus the average duty cycle. This probability is rather high showing that the UMTS uplink band was not highly utilized during our measurement campaign even during the peak hours. In the reference case, the probability of finding free channels is surprisingly higher in case of consecutive bandwidth. This is against the intuition because a continuous block of free bandwidth is expected to appear more seldom. However, although the best combination of non consecutive channels leads to a higher probability of finding free bandwidth, the cases of consecutive bandwidth lead on average to a higher probability of success. This could, e.g., be caused by the wideband nature of wideband code division multiple access (WCDMA) signals such as used by UMTS. The difference between consecutive and non-consecutive bandwidth is largest for a requested bandwidth of about 5 MHz, which is the bandwidth used by UMTS networks. Our measurement traces show that few regulated UMTS channels are not served at our measurement location and frequency bins belonging to these channels have small duty cycles. The number of different sets of consecutive channels is limited and the sets belonging to these unserved UMTS channels increase the average probabilities significantly. Since the number of sets of non consecutive channels is much higher the impact of the sets belonging completely to the unserved UMTS channels on the average probabilities to find the sensed bandwidth free is smaller.

If some historical information is used, the probability of finding free spectrum considerably increases. If a secondary user looks for consecutive bandwidth of 9 MHz his probability of finding such bandwidth free increases by about 70 % by considering the duty cycle. The performance results for the three methods that exploit different historical information are similar. There are nearly no periods below five minutes for the UMTS uplink band so that only very few periods can be exploited for the adaptive sensing based on the periodicities of the primary users' signal. The prediction of the Markov model performs slightly better than the approach based only on the duty cycle so that our expectation that spectrum occupancy is correlated over time and most transmissions last longer than our inter-sample time is correct.

2) Analysis of the GSM uplink band: The GSM uplink is regulated to work within the band 880.1-913.9 MHz in the Netherlands. Figure 2 shows the probability of finding the requested amount of bandwidth free when sensing exactly this amount of bandwidth as a function of the requested bandwidth for this second example. As in the UMTS band analysis, we distinguish two cases: The case of consecutive channels and the case of non consecutive channels. The probability of finding a single free channel in the reference case of about 40 %, which corresponds to the average duty cycle in this band throughout the whole measurement, shows that the GSM uplink band is used more regularly than the UMTS uplink band in our campaign. The higher utilization can also be seen from the fact that consecutive bandwidths found free at least with 50 % probability with the best adaptive technique (Markov model in our case) do not exceed 1.1 MHz. However, the average duty cycle of 40 % in the GSM uplink band still shows that indeed spectrum opportunities are present, except maybe during the peak hours. Typically, GSM networks have been designed to exhibit high occupation during the peak hours with a pre-defined maximum call blocking probability [23].

The periodicity analysis found several signal periods within the GSM uplink band. Little improvements of up to 15 % can be observed by combining the periodicity with the duty cycle instead of using the duty cycle only. This is particular for the GSM uplink case, since the duty cycle has large values. In all the other cases, the gain by considering periodicities is negligible. As for the UMTS uplink band, the Markov-model still leads to superior performance.

3) Comparison to theoretical spectrum occupancy models: Our analysis is based on measured trace data and it would be interesting to confront the results with analytical results from the literature. Only very few approaches have been published on modelling the spectrum occupancy for concrete bands. Authors in [14] generated spectrum occupancy data using a uniform distribution between 0 and 1 for the duty cycles at separate channels. This model seems reasonable because it includes both extreme cases of fully occupied or completely empty channels as we measured, e.g., in the UMTS uplink band.

We calculate the probability to select a free band for sensing with this occupancy model along the lines of section III-A. Results are shown in Figure 3. All curves are based on the duty cycle based strategy for the channel selection. We evaluated either the duty cycles extracted from our measurement traces taken in the UMTS uplink band or generated artificial duty cycle values based on the uniform distribution model as in [14]. In the latter case, 5000 spectrum instances were generated and the results were averaged over all of them. The uniform distribution for duty cycles between 0 and 1 overestimates the duty cycle on average (average duty cycle = 50 % instead of ≈15 %) and leads to very low probabilities of sensing a free channel. In order to make a fairer comparison with our measurements, we also consider the case where the duty cycle is uniformly distributed between 0 and $2 \times \mathbb{E}[DC]$ such that the duty cycle matches with the one of our measured data. The modelling is clearly better but still leads to unrealistically low probabilities of successfully sensing a band free. The main reason for the significant difference is the distribution of the measured duty cycle values. Our measured distribution shows a peak for very low duty cycles and another peak for very high duty cycles and is far from being uniform. The adaptive sensing based on historical information obviously favors the channels with low duty cycles. Since the number of channels with low duty cycle is higher for the measured data than for the model from [14] higher probabilities can be reached when looking for more than only few channels.

The model proposed in [14] was introduced in a slightly different context but the differences between the model and our measurement traces in terms of results point out the importance and also the difficulties of developing generic and realistic spectrum occupancy models for a large multiband spectrum.

IV. Optimal tradeoff between the outage probability and the sensed bandwidth

As demonstrated in the previous section, the risk of detecting a primary user signal and thus failing to find an unused band will be too high in most cases if the bandwidth to sense is limited to exactly the requested bandwidth. One solution consists of increasing the bandwidth to sense. However, it is crucial to limit the sensing operation in order to keep low power consumption. The tradeoff between increasing probability of finding an unoccupied band and increasing sensing costs in terms of time and energy has to be decided upon. In this section we shall introduce a formulation of this problem and a new metric to evaluate the performance of the potential strategies for sensing at low cost. We will accordingly propose several algorithms and present some evaluation results based on our measurement data.

Denote as T and B the requested bandwidth for data transmission and the sensed bandwidth. Additionally, we define W as the working band that can be predetermined by spectrum regulations, policies, or hardware limitations (e.g., GSM1800 uplink band). Without loss of generality, we assume that all these three bandwidths consist of an integer number of consecutive channels of same width. We define $M \in [1 \ldots K]$ as the number of consecutive channels that span the requested bandwidth T starting at index $t_1 \in [1 \ldots K - M + 1]$. Furthermore, denote N as the number of channels that B is composed of, starting at the index $b_1 \in [1 \ldots K - N + 1]$ and denote K as the number of channels in W. The detailed relations of the different bandwidths and numbers of channels are described in Figure 4. Additionally, all the three bandwidths and numbers of channels are connected through the following chains of inequalities:

$$W \geq B \geq T, \quad K \geq N \geq M.$$

In our case, one channel corresponds to a single frequency bin measured by the spectrum analyser. Since the frequency bins measured by the spectrum analyser slightly overlap, the bandwidth covered by consecutive channels is not simply a multiple of the resolution bandwidth $f_{resolution} = 200\,\text{kHz}$.[1] By taking this into account, T, B, and W can be expressed as:

$$\begin{aligned} T &= M \times \frac{1500}{8192}\text{MHz}, \\ B &= N \times \frac{1500}{8192}\text{MHz}, \\ W &= K \times \frac{1500}{8192}\text{MHz}. \end{aligned}$$

A. Determination of the minimum sensed bandwidth required by the transmission of interest

Practically, T represents the bandwidth required by the transmission. For given T and W an adaptive sensing technique has to address the fundamental question of finding the minimal value $\hat{B}$ and the optimal starting index $\hat{b_1}$ such that the probability of finding M consecutive channels within B is high while keeping B as small as possible.

[1] In order to cover the configured span of 1500 MHz 8192 measurement points were used.

We define $p_{outage}(T)$ as the probability that the secondary user will not be able to identify a spectrum opportunity of width T, will have to pause his transmission for at least one sweep time, i.e., 1 sec, and will thus be in outage during that time. The outage probability $p_{outage}(T)$ is directly connected to $p_{free}(T \in B)$ defined in section III-A, i.e., the probability of finding an unused spectrum band T inside B:

$$p_{outage}(T) = 1 - p_{free}(T \in B). \tag{2}$$

Based on the application requirements, a maximum value for the outage probability denoted as $p_{outage,\ max}$ can be defined and used as performance metric during the search for minimal $\hat{B}$:

$$\hat{B} = \min_{N \in [1..K]} B^{(N)}, \text{ such that } \exists\, T \in [B^{(N)}(b_1), \ldots, B^{(N)}(b_{K\text{-}N\text{+}1})], \tag{3}$$

which satisfies $p_{outage}(T) \leq p_{outage,\ max}$. $B^{(N)}$ denotes any bandwidth consisting of N consecutive channels and $B^{(N)}(b_1)$ refers to $B^{(N)}$ starting at frequency bin b_1. The starting frequency $\hat{b_1}$ is determined as the starting frequency which maximises $p_{free}(T \in \hat{B}(b_1))$ over all starting frequencies $b_1 \in [1..K - N + 1]$ that satisfy the outage probability requirement:

$$\hat{b_1} = \max_{b_1 \in [1..K-N+1]} p_{free}(T \in \hat{B}(b_1)). \tag{4}$$

Note that we consider only the outage events due to the interference caused by the primary user and not the additional outage events due to the deep fadings that may occur during the transmission even if the primary user does not transmit.

In order to determine $\hat{B}$ for given $p_{outage,\ max}$ and T, we first determine $p_{outage}(T)$ in (2) which is equivalent to calculating the probability $p_{free}(T \in B)$. We define S_r as the subband which comprises M consecutive channels starting at channel index r to channel index $r + M - 1$ and $p_{free}(S_r) = \prod_{c=r}^{r+M-1}(1 - DC_c)$ as the probability that the whole subband S_r is free. The probability $p_{free}(T \in B)$ corresponds to the probability that at least one subband $S_r \in B$ is free, i.e.:

$$p_{free}(T \in B) = p_{free}\Big(T \in \bigcup_{r=b_1}^{b_1+N-M} S_r\Big). \tag{5}$$

This model is only based on the duty cycle and does not consider the Markov model or the periodicities. Indeed, the duty cycle model provides results almost as good as for the other models in most of the bands of interest at much lower computational complexity. For practical considerations, we also limit our evaluation to the case of consecutive requested bandwidth.

The evaluation of the probability (5) is challenging especially for large N and M and requires some simplifications. First, we assume that the duty cycles of the frequency bins are independent of each other. This assumption is only partially verified in our measured data since the duty cycles of two adjacent frequency bins are likely to be correlated. However, it is essential to use this assumption in order to reach reasonable computational complexity for the evaluation of (5). Additionally, our calculations still use the measured duty cycles and are thus more realistic than purely theoretical evaluations.

By noticing that the events in (5) are not mutually exclusive due to the partial overlapping of their bands (for instance S_1 and S_2 share all indices but one) we can rewrite the sought probability (5) as

$$\begin{aligned} p_{free}\Big(T \in \bigcup_{r=b_1}^{b_1+N-M} S_r\Big) \; = \; & \sum_{i_1=b_1}^{b_1+N-M} p_{free}(S_{i_1}) \\ & - \sum_{i_1=b_1}^{b_1+N-M-1} \; \sum_{i_2=i_1+1}^{b_1+N-M} p_{free}(S_{i_1} \cap S_{i_2}) \\ & + \sum_{i_1=b_1}^{b_1+N-M-2} \; \sum_{i_2=i_1+1}^{b_1+N-M-1} \; \sum_{i_3=i_2+1}^{b_1+N-M} p_{free}(S_{i_1} \cap S_{i_2} \cap S_{i_3}) \\ & \vdots \\ & +(-1)^{j-1} \sum_{i_1=b_1}^{b_1+N-M-j+1} \; \sum_{i_2=i_1+1}^{b_1+N-M-j+2} \cdots \sum_{i_j=i_{j-1}+1}^{b_1+N-M} p_{free}\Big(\bigcap_{h=i_1}^{i_j} S_h\Big) \\ & \vdots \\ & +(-1)^{b_1+N-M-1} p_{free}\Big(\bigcap_{r=b_1}^{b_1+N-M} S_r\Big). \end{aligned} \tag{6}$$

The number of terms in this formulation equals

$$\begin{aligned} & N-M+1 + (N-M+1) \times (N-M) + \ldots \\ & (N-M+1) \times (N-M) \times (N-M-1) + \ldots \\ & + (N-M+1) \times \ldots \times (N-M-j+2) + \ldots + 1 \quad \approx \quad O((N-M+1)!). \end{aligned}$$

Therefore, an exhaustive search over all possible values for N and b_1 is not possible for large N, $N > M$. We further simplify the problem by considering only the subset of the Q subbands S_r, $r \in [1 \ldots N-M+1]$, that maximize $p_{free}(S_r)$. The heuristic applied here assumes that the subbands with high $p_{free}(S_r)$ contribute the most in (6). In our simulations, we calculate $p_{free}(S_r)$ for all available subbands and select the $Q = 20$ indices corresponding to the highest probabilities. Considering 20 subbands out of $N-M+1$ is a good compromise between the accuracy of the approximation and the involved computational complexity.

Regarding the problem of selecting b_1 we compare three strategies:

1) Reference case: We arbitrarily select $b_1 = 1$. This is the reference case because no historical information is used.
2) Best requested bandwidth T: We determine the subband S_x which maximises p_{free} based on the historical information (in our case the duty cycles only) and sense S_x and the $N-M$ channels surrounding S_x ($(N-M)/2$ on the left and $(N-M)/2$ on the right side). As we consider that T has been preliminarily determined based on the requirements for the transmission, $p_{free}(T \in B)$ will monotonically increase with respect to the bandwidth to sense B.

Instead of relying only on the duty cycle information, the strategy could also use other models for the spectrum occupancy, e.g., the Markov chain discussed in section III-A to select the preliminary T. However, the duty cycle based approach performs almost as well as the approach based o the Markov chain and is significantly less complex so that we limit our evaluation to this method.

3) Best sensed bandwidth B: Instead of selecting the subband of size T with the highest probability of being free we determine the subband of width B with the highest probability of being free based on the duty cycle information. This strategy does not prevent that another band $B' \neq B$ might minimize $p_{free}(T \in B')$ whereas $p_{free}(B) \geq p_{free}(B')$. Therefore, the probability $p_{free}(T \in B)$ will not automatically monotonically increase.

B. *Comparison of different strategies to determine b_1*

Figure 5 compares the three strategies for finding $M = 3$ consecutive channels in the GSM uplink band. $M = 3$ corresponds to a bandwidth of approximately 550 kHz. The approaches taking advantage of historical information clearly outperform the reference case for smaller amount of sensed bandwidth. We can further see that the slope for p_{outage} for the *best required bandwidth* strategy is rather constant until the sensed bandwidth reaches about 10.5 MHz. This can be explained as follows. There exists a band of this width around T with lower occupancy than the rest of the investigated band. However, in this band, the occupancy is still pretty high for some channels and varies dramatically from one channel to another, i.e., narrow free subbands succeed to narrow occupied subbands. Increasing the sensed bandwidth B improves p_{outage} in a staircase manner. If the channels, which were just added to the sensed bandwidth B, are part of an occupied subband p_{outage} will remain constant. Reciprocally, if the channels are part of an unoccupied subband, p_{outage} will drop. Increasing the sensed bandwidth leads to the direct improvement of p_{outage} by including one of these partially free subbands after one another. Whereas the performance of the strategy *best sensed bandwidth* fluctuates more with respect to the sensed bandwidth, this strategy is superior compared to both other strategies. This result is specific for the GSM uplink band. For other bands the duty cycle varies less over frequency and spectral opportunities are more clustered. For these cases the *best requested bandwidth* performs at least similarly well or even better. Additionally, for the *best sensed bandwidth* strategy the outage probability does not monotonically decrease. Although the bandwidth to sense was increased the outage probability may also significantly increase. This instability of the *best sensed bandwidth* strategy makes the *best requested bandwidth* strategy the preferred choice that we use in the remaining paper.

C. *Required bandwidth to sense with respect to p_{outage}*

In the next step we investigate the impact of B on p_{outage} for different requested bandwidth T by the application. Figure 6 compares p_{outage} for $M = 1 \ldots 5$ requested channels (from 200 kHz to ≈ 0.9 MHz) in the GSM uplink band. We use here the *best requested bandwidth* strategy.

The nearly constant slope in logarithmic scale for smaller requested bandwidths shows that the outage probability can be arbitrarily small by increasing the bandwidth to sense as long as the requested bandwidth is small. However, for increasing demands in terms of requested bandwidth, e.g., above 0.9 MHz, the outage probability cannot decrease below a certain value, e.g., 10^{-1} for 0.9 MHz, even if we scan the whole GSM uplink spectrum of 33.8 MHz. For instance, in order to use a bandwidth of 0.9 MHz to transmit with outage proabbility $p_{\textit{outage, max}} < 10^{-1}$, a DSA capable system would have to sense at least 15 MHz. For larger sensed bandwidth, no better outage can be achieved. Additionally, the outage probability can even be higher during the peak hours.

D. Comments on the evaluation of further spectrum bands

In contrast to the GSM uplink band, the spectrum occupancy is highly clustered in some other bands. In our measurements, some subbands were highly occupied while some other subbands were free for nearly the whole measurement time. In such scenarios, $p_{\textit{outage}}$ as a function of the sensed bandwidth becomes a step function. As soon as two of the nearly free subbands are covered by the sensed bandwidth B, $p_{\textit{outage}}$ will suddenly drop further compared to the case when only one subband is covered. As the bandwidth of each of these two subbands has to be at least T, the decreasing of $p_{\textit{outage}}$ as function of the sensed bandwidth is irregular. In such scenarios, schemes supporting transmission over non continuous spectrum will be more efficient. In our measurements, we observe this phenomenon in the UMTS uplink band for instance.

Figure 7 shows a similar graph for the GSM1800 uplink band. Some of the outage probabilities do not seem to reach 10^{-5} (2, 3, 5, 8.1 MHz) because their corresponding probability for larger sensed bandwidths drops to 0 and cannot be represented in the logarithmic scale anymore. Besides the curve for $T = 10.1$ MHz, the outage probability goes down to 0 as soon as more than about twice the required bandwidth is sensed. However, this relationship cannot be generalised to arbitrary band in the whole 20 MHz-3 GHz considered in our measurement campaign because it heavily depends on the investigated spectrum window. The historical information should thus be exploited in order to differentiate these cases and enhance the sensing behaviour appropriately.

E. Combination of several bands during the sensing process

Until now we evaluated each frequency band separately. Since most of the wireless devices have the capability to transmit in multibands (GSM + UMTS + ISM for instance), it is also interesting to consider sensing units that combine different spectrum bands. Figure 8 shows the required sensed bandwidths for three selected outage probabilities and a requested bandwidth of $T = 3$ MHz also for different combinations. We consider that the overall sensed bandwidth is equally shared among all considered bands. For example, if the sensed bandwidth is $B = 10$ MHz and two spectrum bands are investigated, in each band the optimal bandwidth of 5 MHz will be sensed. We used the *best requested bandwidth* strategy to select these optimal subbands.

In this figure, we do not incorporate results with the GSM uplink band. This band is highly occupied and neither sensing only this band nor any combination of bands with this band can match the performance of the other considered bands. We consider the GSM1800 uplink band, the UMTS uplink band and the unlicensed spectrum band reserved for industrial, scientific and medical (ISM) applications at 2.4 GHz. Figure 8 shows that sensing single bands yields always better performance than sensing multiple bands. We can indeed sense larger consecutive blocks of spectrum. Some combinations perform also well (ISM + UMTS for instance) but the minimum required amount of sensed bandwidth B to provide the requested $T = 3\,\text{MHz}$ is higher than in the case of single bands because the sensed spectrum is equally split between the bands.

V. Conclusions

In this paper we analysed several adaptive sensing techniques. We have validated these strategies on data from an extensive measurement campaign. All presented results are thus based on real-life measurements. We have compared four methods for predicting free channels in the next time lag. We exploited historical information in form of the estimated duty cycle and the periodicities of the signals. Additionally, we used a first order Markov chain to model the temporal correlation of the spectrum occupancy. Based on the small number of short periodicities, exploiting periodicity information yields rather small gain. Whereas the Markov chain is superior in most cases, the purely duty cycle based model performs very well at low cost. As the duty cycle based model performs especially well for rarely used bands, which are also the most attractive ones for DSA capable systems, more complex models are rarely required for DSA. However, we also showed that the distribution of the duty cycle is crucial for the system performance and has to be modelled accurately.

As a second step, we introduced the outage probability p_{outage} as a performance metric for comparison of sensing techniques. We formulated the problem of determining the minimum bandwidth to sense such that the outage probability is equal to or less than a threshold $p_{outage,\,max}$. In order to evaluate the true gains in real-life scenarios, we evaluated the impact of the sensed bandwidth on p_{outage} based on the measurement data. The results show that exploiting historical information dramatically improves the selection of the bandwidth to sense. In GSM bands, we however observe that increasing the sensed bandwidth cannot reduce the outage probability as long as the requested bandwidth T exceeds 1 MHz. In theory, the optimal adaptive sensing technique would exploit historical information in order to first differentiate such scenarios based on the application requirements and select the bandwidth to sense appropriately.

We will further enhance the schemes in our future work and plan to investigate wideband systems capable of sensing discontinuous frequency bands that could also be spread over large amounts of spectrum. Also the determination of short-term historical information, that can be exploited for specific periods (for instance peak hours) remains an open problem. Furthermore, we will evaluate the minimum amount of observations needed to correctly estimate the historical information.

In addition to these algorithmic aspects, we will work on more realistic models for spectrum occupancy based on the results of our intensive measurement campaign. Particularly, we will pay special attention to the correlation of spectrum occupancy over time and frequency.

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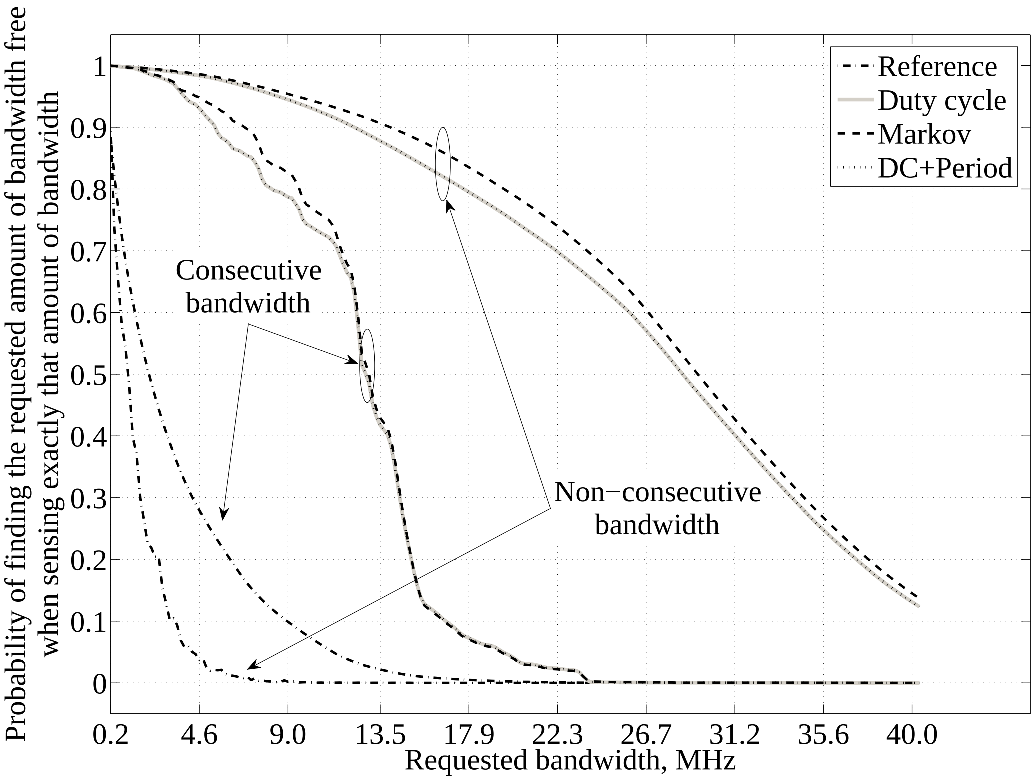

Fig. 1. Comparison of the four methods for adaptive spectrum sensing for the UMTS uplink band. The curves for duty cycle and DC+Period cannot be easily distinguished because of the negligible impact of periods and, thus, a very small difference between them.

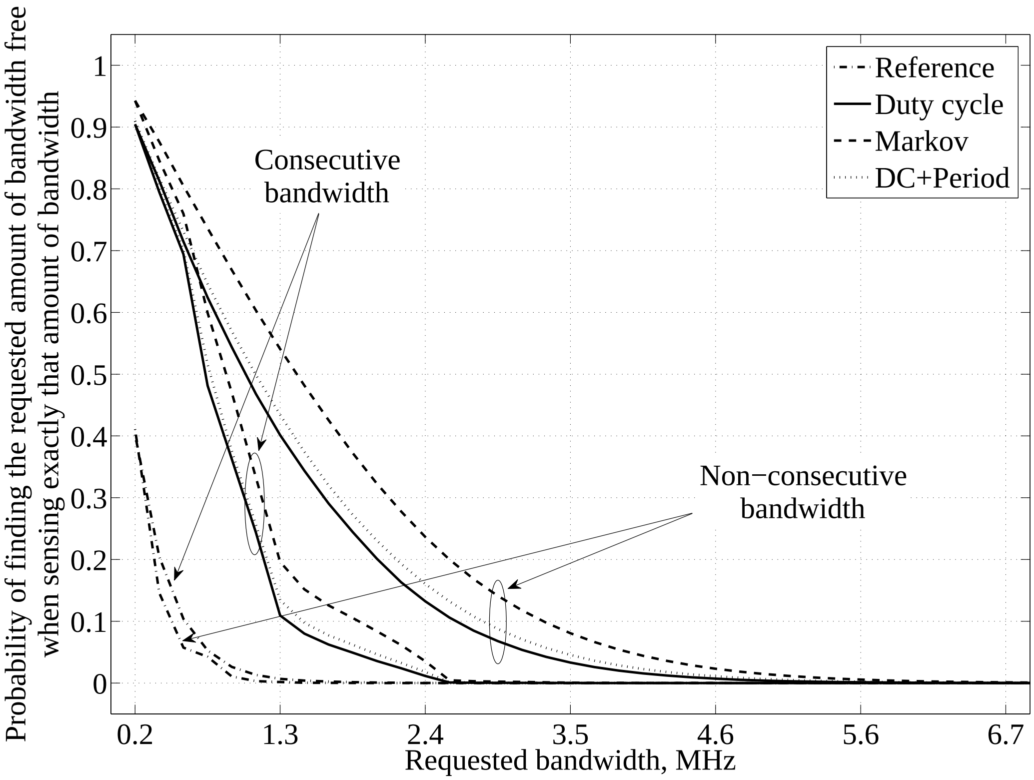

Fig. 2. Comparison of the four methods for adaptive spectrum sensing for the GSM uplink band.

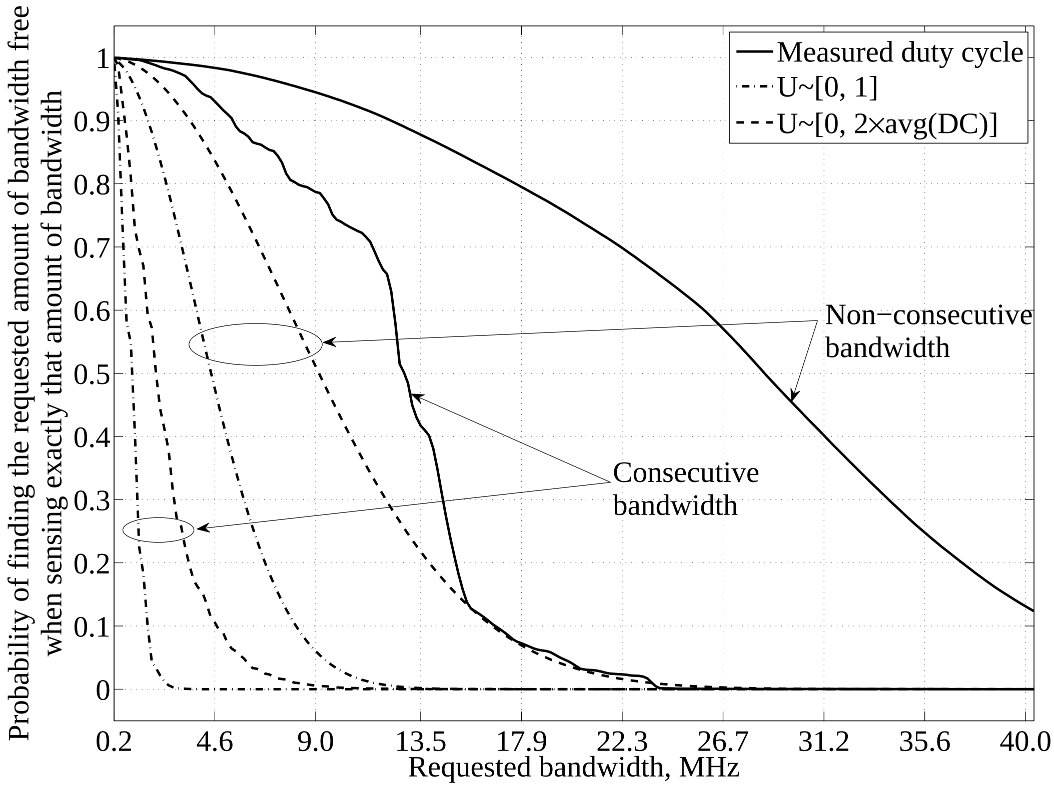

Fig. 3. Comparison between the duty cycle measured in the UMTS uplink band and artificial spectrum occupancy data generated based on the model described in [14].

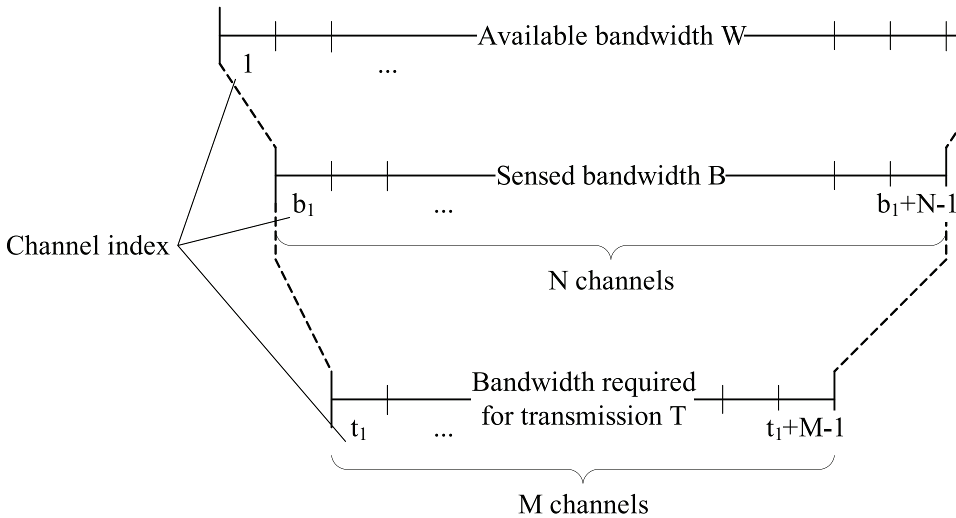

Fig. 4. Relations of the different bandwidths and numbers of channels used throughout the formulation of the tradeoff between the outage probability and the sensed bandwidth.

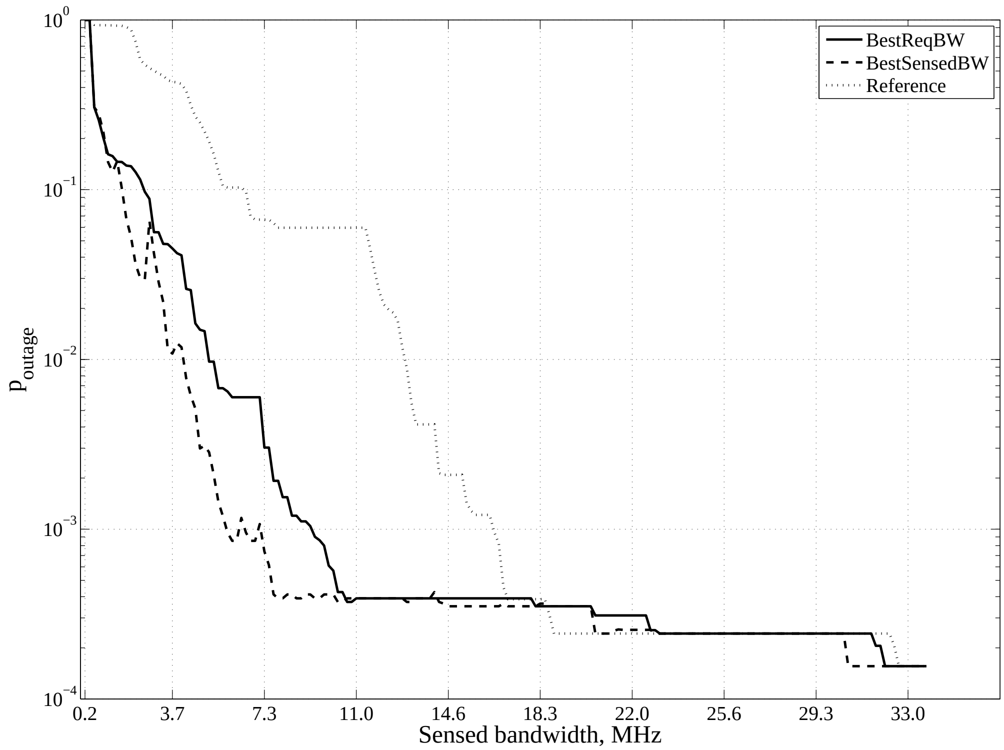

Fig. 5. Comparison of the three strategies for selection of b_1 for the GSM uplink band and $T \approx 550\,\text{kHz}$.

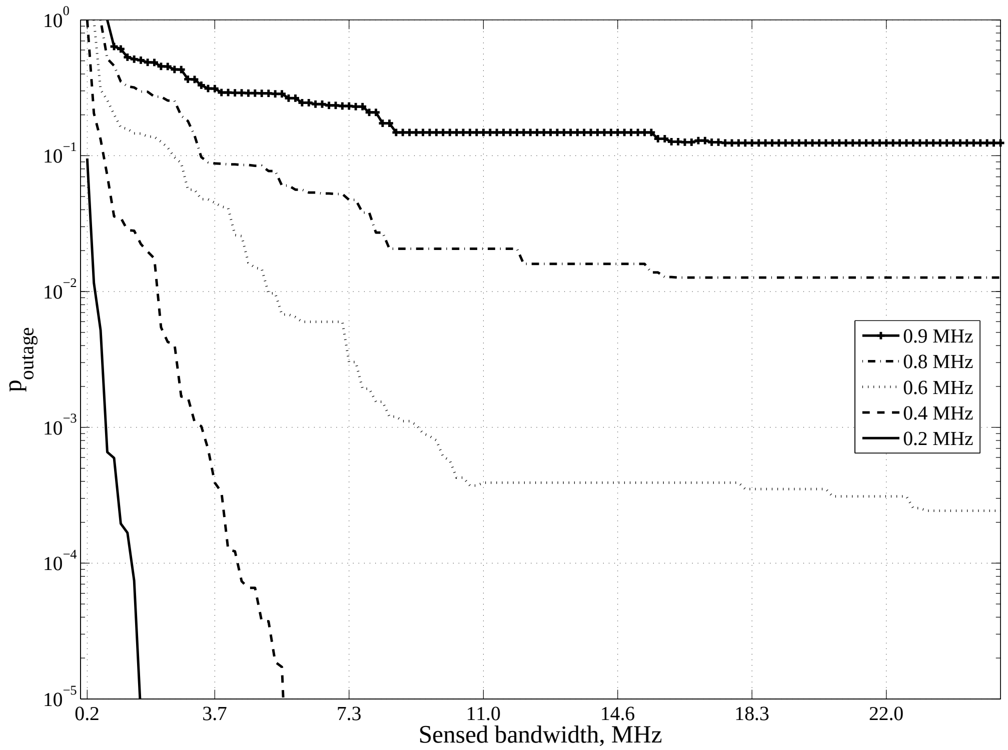

Fig. 6. Impact of sensed bandwidth B on the outage probability p_{outage} for the GSM uplink band.

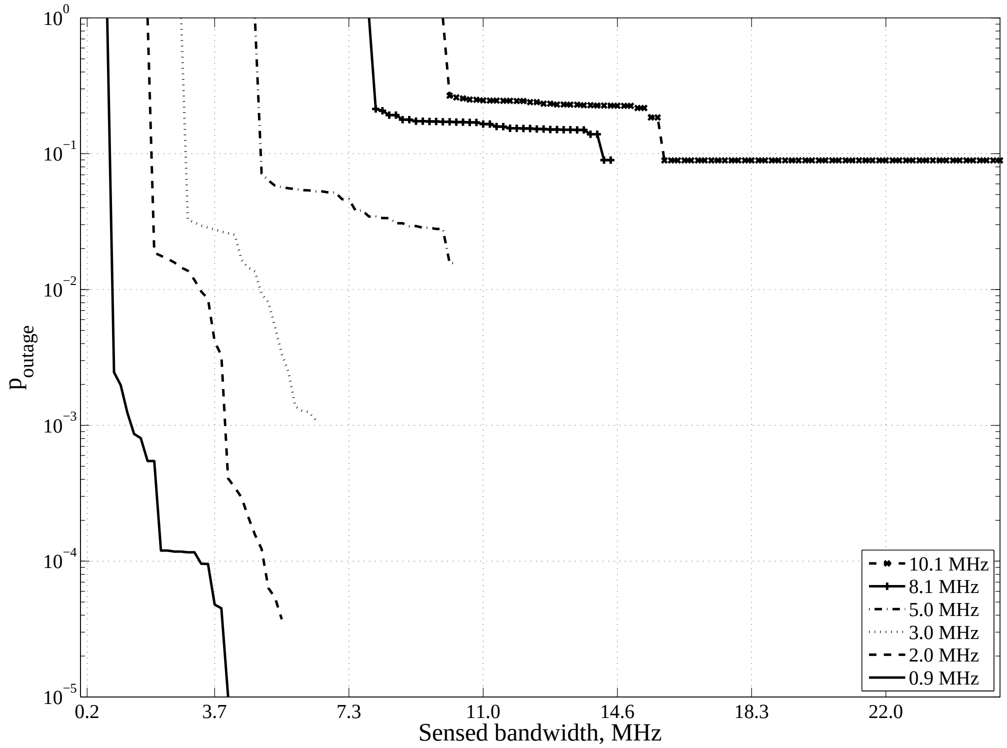

Fig. 7. Impact of sensed bandwidth B on the outage probability p_{outage} for the GSM1800 uplink band. Curves that stop reached 0 and cannot be represented in logarithmic scale anymore.

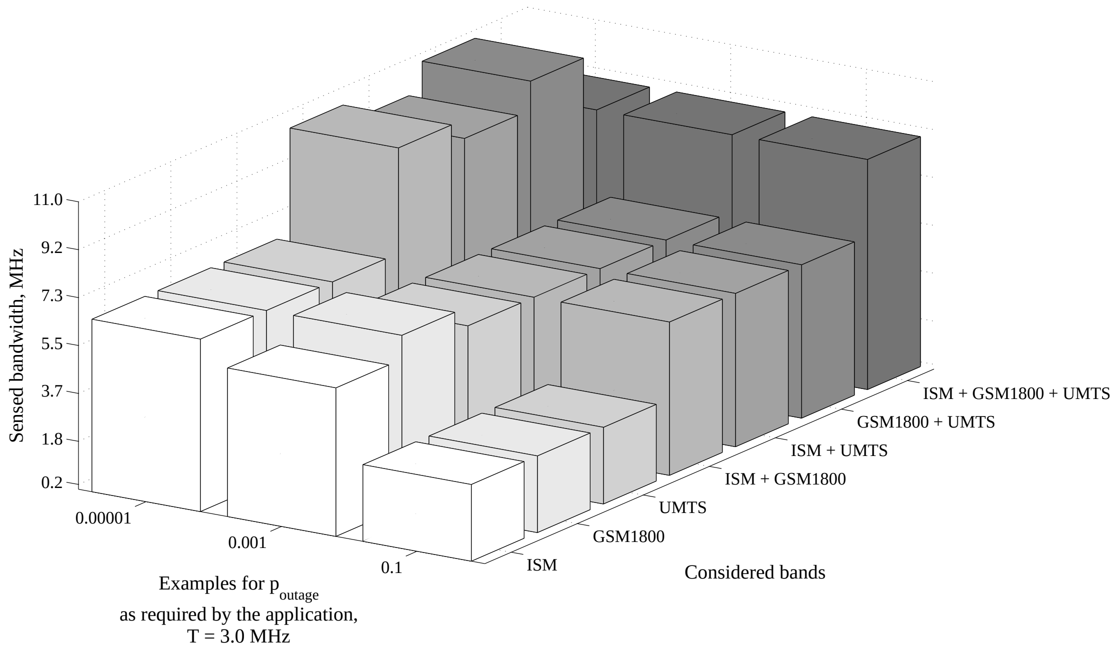

Fig. 8. Impact of sensed bandwidth B on the outage probability p_{outage} in several bands: ISM, GSM1800, UMTS, or combination of some bands: ISM + GSM1800, ISM + UMTS, GSM1800 + UMTS, ISM + GSM1800 + UMTS. Three target outage probabilities are considered: 10^{-1} (voice quality), 10^{-3}, 10^{-5}.