Measurement-Efficient Dynamics Change Detection in On-Off Models for Dynamic Spectrum Access

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***Abstract*—To maintain efficient scheduling for dynamic spectrum access problems, it is crucial to promptly detect changes in the statistical properties of spectrum occupancy. Compared to traditional change detection problems, this is complicated by the fact that measurements are not independent through time and can instead have Markovian dependencies. Moreover, classical change detection methods neglect the cost associated with measurements and do not consider the potential benefits of adapting the measurement schedule based on the observed state and the perceived likelihood of a change. This may result in high measurement overhead. In this paper, we study measurement-efficient change detection in Markovian models and demonstrate its applicability for spectrum access problems. In particular, we study problems with two states corresponding to spectrum occupancy, so called *on-off* models, and show important properties of these problems. For these problems, we establish fundamental limits that are imposed when the detection agent must maintain a sufficiently small false alarm rate. We also propose two classes of algorithms designed to adapt to different aspects of the problem. We analyze the behavior of these algorithms and evaluate them, using both synthetic data as well as real Wi-Fi spectrum data.**

I. Introduction

Due to the scarcity of radio spectrum, it is vital to efficiently utilize radio spectrum without causing conflicts in transmission. To this end, Dynamic Spectrum Access (DSA) is useful, thanks to its ability to compact secondary users into the gaps left by primary users, and it is a promising technology for spectrum management [1]. However, any DSA algorithm will make assumptions about the dynamics of the spectrum, and these dynamics can sometimes change rapidly. While the spectrum can be monitored to detect such changes, this monitoring induces costly overhead such as power consumption in the sensor, as well as costs of data storage and management.

In this paper, we study a DSA scenario where a change detection agent wishes to detect a change as soon as possible without raising too many false alarms,

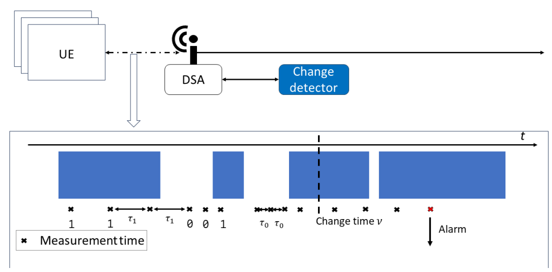


Fig. 1. The change detection agent communicating with a DSA algorithm. Also illustrated: typical spectrum behavior and measurement sequence, where the blue blocks represent the busy periods of the spectrum. The static measurement policy defined in Section II is also shown.

and without taking more measurements per time unit than necessary. This is illustrated in Figure 1. The detection agent observes the spectrum by communicating with a DSA agent in an access point or base station, and raises an alarm to the DSA agent when a change is detected. However, spectrum occupancy is typically independent of earlier occupancy given the current occupancy, which as such can be modeled as a Markov chain. In addition, we are interested in devising *data-efficient* detection schemes, i.e., limiting the number of taken measurements. Existing approaches [2], [3], [4] all tend to measure very often when they believe a change has occurred, allowing for fewer measurements otherwise. These approaches would fail in case of Markovian dependence, as this would lead to vastly inefficient measurements being taken, even when no change has occurred. This is an extended abstract, with the full paper accepted for publication at IFIP NETWORKING 2025.

II. Approach, Algorithms and Analysis

In this paper, we consider an extension to the two-state Markovian change point detection framework where the agent, after receiving measurement $X_n \in$

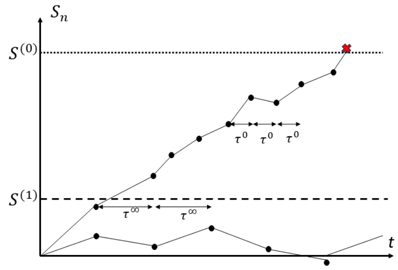
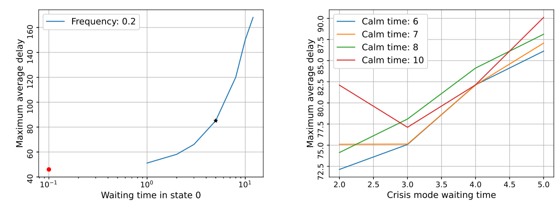


Fig. 2. Evolution of the CUSUM statistics pre-change and post-change, when measurements are taken according to a CUSUM-threshold policy.



(a) Static (b) CUSUM

Fig. 3. Worst case average delays for different static policies and CUSUM-threshold policies. The red dot marks optimized parameters and the black star marks periodic measurement schedules.

$\{0, 1\}$, also decides on the next measurement interval $\tau_{n+1} \geq 0$ along with the stopping time, or detection strategy, N. It will thus stop and raise an alarm at time $t_N = \sum_{n=1}^{N} \tau_n$. A change in transition dynamics (λ, μ) occurs at time $\nu \in [0, \infty]$. To avoid floods of false alarms, we consider only agents meeting the average run length to false alarm (ARL) $\mathbb{E}_\infty[t_N] \geq \gamma$, where γ is set by the operator.

The Markov nature of the problem allows us to only study two aspects of the system state. One of them is the last observed spectrum state X_n and the other is the Cumulative Sum (CUSUM) statistic of the change detection problem [5], [6]. While an optimal agent would likely use both of these aspects, it is of particular interest to study agents which use only one aspect each - using the state yields *static policies* as shown in Figure 1 while using the CUSUM statistic yields *CUSUM-threshold policies* (shown in Figure 2), which wait for some calm time τ^∞ when the CUSUM statistic is small and for crisis time $\tau^0 < \tau^\infty$ otherwise.

Our first theoretical contribution is showing that no agent with $\mathbb{E}_\infty[t_N] \geq \gamma$, regardless of measurement frequency, can detect changes faster than

$$\mathbb{E}_\nu\left[(t_N - \nu)^+\right] \geq (d(0) + o(1)) \log \gamma$$

as $\gamma \to \infty$. Here, $d(0)$ is a constant which only depends on the pre-change and post-change transition rates of the Markov chain. The second theoretical contribution is a similar lower bound for any static policy $\boldsymbol{\tau} = (\tau_0, \tau_1)$, with the constant $d(0)$ replaced by the function $d(\boldsymbol{\tau}) \geq d(0)$ for all $\boldsymbol{\tau} \geq 0$. Furthermore, we also show that with a good choice of stopping rule, the lower bound is met and we can therefore optimize to find the static policy with the smallest detection delay subject to any pre-change measurement frequency and average run length to false alarm.

III. Numerical evaluation

To evaluate the performance of our algorithms compared to a benchmark on a spectrum access scenario, we studied data generated by a Wi-Fi access point programmed to sense the usage of a Wi-Fi channel. We studied the usage of a channel on a work day where after a brief period of moderate to high utilization (36%), the work day ended and the utilization drops to $< 0.1\%$. We evaluated several choices of parameters for static and CUSUM-threshold policies, subject to the same ARL and pre-change measurement frequency. The results for both policies is found in Figure 3.

The optimized static policy is quite far away from the fixed period policy and also outperforms CUSUM-threshold policy. While this policy does sample more often than the true sampling rate $\tau_{min} = 1$ ms, the same properties are true if one constrains the policy to staying within these bounds. While these results imply that static policies are more efficient compared to CUSUM-threshold policies, the results in our full paper show a more nuanced picture with the CUSUM-threshold policies sometimes being more efficient.

Acknowledgements

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