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Goodput maximization in opportunistic spectrum access networks under constraints on the inter-packet transmission waiting time

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ABSTRACT

We consider the problem of selecting the packet size, the Forward Error Correction (FEC) coding rate, and the duration of the spectrum sensing interval, which maximize the communication goodput (payload bits correctly received per unit time) of the Secondary Users (SUs) of a cognitive radio network. We start by deriving a closed form expression of the SUs achievable goodput under the assumption of Markovian primary channel use and perfect spectrum sensing. Then, we show that the optimal packet size and FEC coding rate selection change in case we impose a constraint on the maximum time SUs can wait before successfully transmitting a packet, i.e., on what we call the inter-packet transmission waiting time. Such waiting time depends on the alternating PU presence on the channel. Finally, we derive upper and lower bounds on the achievable goodput, which allow us to optimally select the packet size, the FEC coding rate, and the duration of the spectrum sensing time interval, in case of imperfect spectrum sensing. Extensive simulation results are provided that validate our findings. Specifically, we show that by adaptively and jointly selecting the system parameters as a function of received SU power and PU traffic statistics, it is possible to achieve a goodput increase in the order of 20%.

1. Introduction

Cognitive radios have been introduced to increase efficiency in the radio spectrum usage [1–3]. In Cognitive Radio Networks (CRNs), Secondary Users (SUs) are allowed to use spectral resources licensed to Primary Users (PUs) provided that they do not cause excessive interference to PUs. By performing spectrum sensing [4,5], the SUs acquire knowledge about the status of the channel and, if unused by the PUs, they access it opportunistically. To keep the interference to PUs at a minimum, if a transmitting SU becomes aware of the beginning of a new PU transmission, it must abort its own. A popular technique to enable SUs to release the PU channel, consists of periodically sensing the channel while transmitting a packet, in a sense-then-transmit way [6–8]. As soon as a PU transmission is detected the channel is vacated by the SU.

At the same time, SUs should fill spectrum holes leaving the channel unused for the smallest possible amount of time. This can be done by carefully selecting the packet size, which defines the granularity with which spectrum holes are filled. Previous works on throughput maximization in CRNs typically consider all transmitted bits in the performance metric, i.e., throughput, without distinguishing payload bits

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from overhead. However, the percentage of packet overhead, which is higher for smaller packet sizes, and the fraction of time devoted to spectrum sensing, has a non-negligible impact on *goodput* (payload bits delivered per unit time). It is important to distinguish between overhead that does not depend on packet size (e.g., packet headers and trailers) and overhead proportional to the payload size, like the redundancy bits for Forward Error Correction for a given FEC coding rate. The role played by the selected FEC coding rate is important since its interplay with the packet size has a direct effect on goodput: for a given FEC coding rate, the smaller a packet, the lower the Packet Error Rate (PER), i.e., the higher the percentage of packets correctly received. However, large packets reduce the percentage of the constant-size overhead at the price of increased PER and coarser granularity in filling spectrum holes, resulting in a larger (on average) waste of resources in case of aborted packet transmissions.

In this work, we focus on the goodput maximization that can be obtained through the optimal selection of packet size, FEC coding rate, and spectrum sensing time, considering all components of the packet overhead. Particularly, we provide the following contributions and results:

1. Under the assumption of perfect spectrum sensing, we compute the SU achievable goodput as function of the operating conditions of the SUs, namely, the SU Signal to Noise plus Interference Ratio (SNIR) and the PU traffic statistics. This result allows us to jointly optimize packet size and FEC coding rate in single channels[2]. Our derivations are based on results of the theory of recurrent events [9].
2. We consider the presence of an outage constraint on the SU inter-packet transmission waiting time[3] defined as the time lasting between two adjacent SU packet transmissions. We aim at selecting the system parameters which maximize goodput while fulfilling the constraint. We solve the problem by computing a closed form expression of the probability mass function (PMF) and complementary cumulative distribution function (CCDF) of the waiting time between adjacent SU packet transmissions. The expression is exact for values of the waiting times up to two times the packet size and closely approximates the CCDF for larger values. Asymptotically, the approximate expression converges to the actual CCDF. Using this result, we show how to modify the goodput-optimal selection of the system parameters.
3. We consider spectrum sensing errors, showing their effect on the achievable goodput. In particular, they affect *both* the way the PUs activity is perceived by SUs *and* the SU PER. We show that in the case of non-negligible spectrum sensing errors the closed form expression for goodput cannot be used in practice. Instead, we provide lower and upper bounds on goodput that can be used for packet size, FEC coding rate, and spectrum sensing interval selection.
4. We show the benefits of adaptive parameter selection under (i) time-varying PU traffic statistics (ii) time varying SNIR (e.g., due to user mobility or channel fading), (iii) diverse multiple SUs and PUs location. Particularly, for the latter case, we average the performance over a cell with randomly spread SUs and PUs. We show that the performance gain achieved by selecting the system parameters adaptively as a function of actual conditions, as opposed to a fixed choice based on nominal conditions, can be considerable.

[2] For simplicity, our analysis is carried out considering a single channel. While many CRN applications rely on the availability of multiple channels, focusing on a single channel allows us to obtain the first results, to the best of our knowledge, based on the theory of recurrent events applied to CRNs. Although outside the scope of our work, an extension of our results to a multichannel set up is possible, and we will consider it for future research.

[3] The outage constraint imposes that the inter-packet transmission waiting time be below a predefined threshold with a desired (close to one) probability.

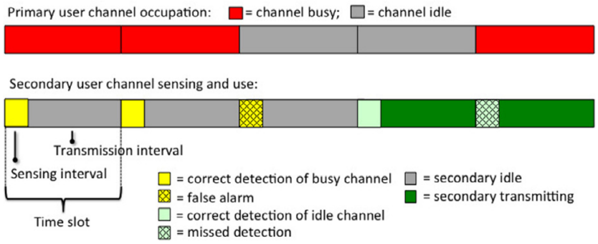

Fig. 1. Channel use of primary and secondary users.

The rest of the paper is organized as follows. Section 2 introduces our system model and assumptions for PU and SU operations, including spectrum sensing and PU traffic modeling. In Section 3 we derive our analytic results for optimal selection of FEC coding rate, packet size, and sensing interval duration, with or without outage constraints on the inter-packet transmission waiting time. We first derive results for the case of negligible sensing errors and then consider the impact of imperfect spectrum sensing. Section 4 presents extensive simulation results to validate our analytical findings. Section 5 positions our work with respect to the literature, highlighting the novelty of our contribution. Finally, Section 6 concludes the paper.

2. System model

We consider the opportunistic channel access scheme described in Fig. 1. SUs follow a sense-then-transmit approach [6–8]: time is divided into slots of duration T_s. At the beginning of each slot, there is a small sensing interval of duration τ_s in which SUs perform spectrum sensing (and do not transmit) to detect PUs signals, followed by a transmission interval of duration $T_s - \tau_s$.

If a secondary transmitter (STx) has a packet to send it senses the channel. If the channel is idle the STx starts transmitting the packet. While transmitting it senses the channel at the beginning of each slot, vacating the channel as soon as a PU transmission is detected. If the packet transmission cannot be completed the whole packet (including preamble and header) has to be retransmitted once the channel is found idle again.

The sensing interval τ_s is small enough (very few symbols) to let a secondary receiver (SRx) keep synchronisation with the SU signal during a SU packet transmission (that lasts for several slots).