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Multimedia over cognitive radio networks: Towards a cross-layer scheduling under Bayesian traffic learning

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A B S T R A C T

Mobility and spectrum change of the cognitive radio networks (CRNs), make the traffic information exchange among the secondary users (SUs) a high-overhead task. In order to quickly estimate the queuing delay in the multimedia over CRN applications without exchanging traffic information among SUs, we are the first group to propose the use of Dirichlet-prior based fully Bayesian model in each individual SU to automatically update its statistical distribution on other SUs' Non-Contiguous (NC)-OFDM subcarrier selection strategy. Such a statistical distribution is used to estimate the probability of queuing delay being less than a threshold. In addition, we introduce a new concept called the Time Window, to accurately determine how many packets can be transmitted simultaneously over multiple subcarriers. Then, we propose a comprehensive, intelligent cross-layer scheduling scheme that can generate the optimal subcarrier selection, power and modulation allocation for each multimedia packet. Our experiments on real video transmission validate our intelligent cross-layer scheduling schemes. The simulation results match with theoretical analysis very well, and the reconstructed video quality using our proposed scheduling scheme is superior to four other popularly used schemes.

1. Introduction

The existence of the under-utilized licensed spectrum in many places has motivated the interest in the cognitive radio networks (CRNs) and dynamic spectrum access [1–3]. In a CRN, the devices can gain access to more wireless bandwidth through opportunistic use of idle spectrum [3,4]. This drives the need of ever-increasing wireless bandwidth, which could span hundreds of MHz to many GHz. However, in such a wide spectrum there could be some narrowband devices which make the available frequency band non-contiguous. To address this problem, authors in [5] proposed a Split-Wideband Interferer Friendly Technology (SWIFT) using Non-Contiguous OFDM (NC-OFDM) based PHY layer. Its main feature is spectrum aggregation – the ability to build high-throughput wireless links by collecting non-contiguous unused spectrum bands that vary the patterns when narrowband devices enter or leave the radio environment [5]. In NC-OFDM system, we can modulate information symbols to subcarriers that are unoccupied by Primary users (PUs), while modulate "0" symbols to subcarriers that PUs are using. Through this method, we can collect non-contiguous, idle spectrum bands. The NC-OFDM multi-carrier access was studied in [5]. SWIFT is shown to be narrowband-friendly, and its throughput is 3.6–10.5× higher compared with the traditional cognitive radio system that coexists with narrowband devices by operating below their noise level [5–7].

However, SWIFT must address a key challenge in order to achieve its goal of high throughput, that is, how does the PHY layer operate across chunks of non-contiguous frequencies? In this paper, we address this challenge and propose an intelligent cross-layer scheduling scheme in a cluster-based CRN. Such intelligence is achieved through the automatic learning of node traffic statistics via a Dirichlet distribution based fully Bayesian model. Thus we can avoid frequent traffic information exchange among nodes. This is especially useful in a mobile CRN environment where the traffic statistics could have significant changes from time to time due to the frequent routing topology changes. The clustering algorithm has been a hot topic, which has been investigated well,

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such as *Max Node Degree* clustering algorithm, *Lowest ID* clustering algorithm, *Distance-based* clustering algorithm, and *Node importance degree* based clustering algorithm [2].

In a CRN, the clustering can reduce the network scale and thus the routing protocol overhead [2,8]. The cluster heads (CHs) are responsible for the data collection from its member nodes (also known as secondary users (SU)), and then they forward to other CHs. Hence, it is challenging to share the available frequency bands among member nodes and dynamically schedule the limited power and modulation scheme of each member node over each subcarrier in NC-OFDM based CRN. *Cross-layer* design in our paper means learning the PHY-layer environment and considering the requirement of multimedia transmission, in order to generate the optimal scheduling, including the subcarrier selection, power and modulation allocation.

Lately, several research results have appeared for the OFDM-based CRNs. In [9], the effect of sensing errors (considering raw sensing information (RSI)) on OFDM based CRN was discussed, which adopted multi-band joint detection to improve the dynamic spectrum utilization and reduce the interference to PUs. A smart acknowledgment (ACK) scheme for broadcast messages was proposed in [10], which adopted OFDM (multi-carrier modulation techniques) to allow the access point (AP) to receive ACKs from a large number of clients in the shortest time, in order to dramatically reduce the time of collecting reliable ACKs. In [11], an in-band solution was proposed to inform receivers about the spectrum usage patterns, by designing an appropriate preamble sequence for NC-OFDM system. Routing protocols were proposed for OFDM-based CRN to obtain a high network performance (in terms of packet delivery ratio and bit error rate) in [12,13]. In [14], a joint cross-layer scheduling and spectrum sensing was proposed for OFDMA-based CRN, which found out the optimal user selection and optimal power allocation to maximize the downlink throughput, considering the RSI and channel state information. In [15], a suboptimal dynamic learning algorithm for multimedia applications was proposed, and the delay and throughput-based utility function was introduced to estimate the quality of service (QoS) of multimedia transmission. The SU collected the required information from other SUs through the priority virtual queue interface, which can be a common control channel (CCC) or out-band mechanism [15]. However, the channel congestion and dynamic power/modulation allocation were not considered in dynamic scheduling. The high-priority SU can preempt low priority SUs without negotiation in [15], which may not be realistic in many applications. The dynamic least interference algorithm was proposed in [16], where the SUs exchanged information about the channel selection strategy of each packet through the CCC, and dynamically selected an idle channel for a new packet (see "Rule C"). This algorithm has the following drawbacks: it needs frequent information exchange to determine the amount of waiting packets in each queue, which can cause CCC congestion and extra delay; Moreover, it only considered delay performance without paying attention to multimedia throughput.

Recently, the QoS-oriented cross-layer designs were proposed for OFDM-based CRNs. For example, in [17], a novel cross-layer scheduling algorithm was proposed to minimize average packet delay and maximize network throughput under constrained transmission power. Each SU can access only one subcarrier, and the convex optimization was used in [17]. Different from [17], we have considered dynamic multi-carrier access and modulation allocation. In [18], efficient power allocation and congestion control were jointly considered in OFDM-based multi-hop CRNs. A nonlinear non-convex optimization algorithm was proposed to minimize energy consumption. The optimal cross-layer scheduling needs extra distributed information exchange, which can bring a high overhead [18]. Unlike such a work, we have introduced Bayesian learning model to predict the dynamic spectrum availability, and made an optimal scheduling decision. In [19], a novel framework was proposed to deal with the channel impairments by dynamically switching among different spectrum bands. It can support QoS for smart grid applications. However, in their work, dynamical modulation scheduling is not considered and distributed information is needed, which are different from our work. In other related works [20–23], throughput-enhanced cross-layer scheduling algorithms were proposed for CRNs, where distributed information exchange was needed in cooperative scheduling; and [24] proposed a cross-layer allocation scheme for delay sensitive service in OFDMA system.

In summary, the essential differences between our research and the previous works include: (1) raw spectrum sensing, queue model, interference temperature, and limited transmit power are all considered in delay and throughput-based utility function; (2) we have used the Bayesian model to learn the dynamic radio environment, thus we avoid the overhead for distributed information exchange in cooperative scheduling.

Although the above mentioned schemes try to solve the scheduling problem in OFDM-based CRN, they have the following significant drawbacks: (*a*) they do not comprehensively consider the following five factors in scheduling design: raw spectrum sensing, channel impulse response (CIR), queue congestion, interference temperature, and limited transmit power; (*b*) Since multi-subcarrier transmissions are used in NC-OFDM system, any subcarrier with interference or conflict will cause bit errors and packet loss. In NC-OFDM system, there is no use of ACK feedback according to IEEE 802.11 PHY protocol [10]. Since the transmitter may not know which subcarrier has conflict or interference, an exponential back-off time will be incurred. This will waste wireless bandwidth and introduce extra-delay, which may not be tolerable in multimedia transmissions [3]; (*c*) Distributed subcarrier selection is considered as a low-complexity scheme compared with centralized schemes [25,26]. However, distributed information exchange among SUs may introduce significant overhead and need a wideband control channel; (*d*) Synchronization is not considered among SUs, which can cause interference and reduce the throughput of NC-OFDM cognitive radios; and (*e*) Conventional dynamic cross-layer scheduling schemes do not consider joint channel and modulation allocation under limited transmission power. As we know, the optimal power consumption requires the adjustment of modulation strategies based on different channel gains and traffic profiles.

In this paper, we propose an intelligent cross-layer scheduling scheme in NC-OFDM based CRN to overcome the abovementioned drawbacks for multimedia transmissions. Our main contributions are following:

(1) To the best of our knowledge, this is the first work that uses a machine learning scheme, called Dirichlet-prior based fully Bayesian model, to achieve dynamic cross-layer scheduling for multimedia transmission in CRNs. When considering any individual SU, we group together other SUs in the same cluster as a virtual node and further propose to use the fully Bayesian model to learn the subcarrier selection strategy of the virtual node. Thus any SU can implicitly deduce other SUs' traffic statistics (in the same cluster). By doing this, we can avoid the high-overhead, frequent traffic information exchange among the SUs from time to time.
(2) We propose to integrate queuing theory with the fully Bayesian model to derive the closed-form result of delay-based utility function. We first use the $M/G/1$ queue analysis and the Pollaczek–Khinchine formula [27] to derive the packet waiting time in a queue. Then, based on the fully