Some Cross-Layer Design and Performance Issues in Cognitive Radio Networks

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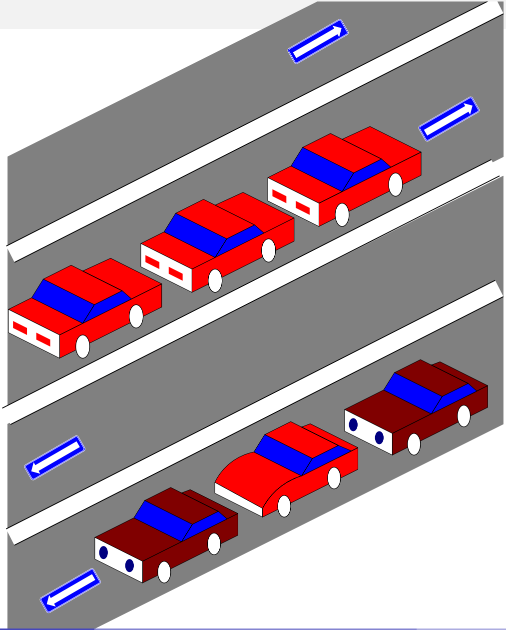
Outline

Introduction



Fixed Spectrum Access

- A certain portion of radio spectrum is allocated/reserved for a certain group of users usually referred to as primary users (PUs)
- Other group of potential users, usually referred to as secondary users (SUs) are not allowed to access the spectrum, even if a particular portion of the spectrum is currently not being used by the PUs
- Recent studies on spectrum measurements have revealed that a large portion of the assigned spectrum is used sporadically by the PUs

Dynamic Spectrum Access

- SUs can share the assigned spectrum with the PUs opportunistically
  - Underlay method
  - Overlay method

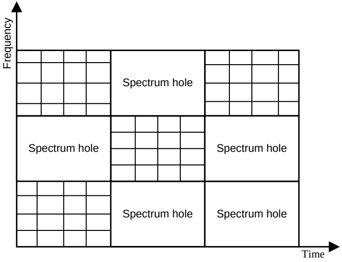


Figure 2: An example of overlay spectrum access with spectrum holes

Cognitive Radio

- Facilitate dynamic spectrum access
- Joseph Mitola proposed the concept of cognitive radio (CR) technology in 1998
- Senses the spectrum of the PUs
- Adapts various transmission and operating parameters including the frequency range, modulation type, and power according to the wireless environment

Motivations

- Wireless channel quality not only varies with time but also the availability of radio spectrum depends on PUs' activity
- Multi-class services e.g., video conferencing, email transfer and web browsing have diverse quality of service (QoS) requirements in terms of delay and packet loss probability
- One design challenge: How to develop innovative resource allocation mechanisms that can meet diverse QoS requirements of different classes of services transmitted over the cognitive radio network (CRN)
- Another design challenge: Channel sensing errors

CRN Architecture: Infrastructure-Based

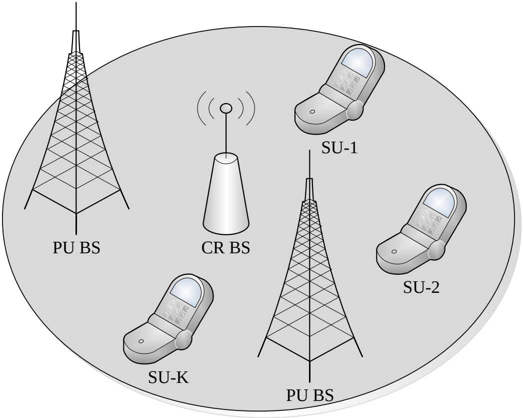


Figure 3: Infrastructure-based CRN, CR=cognitive radio, BS=base station, PU=primary user, SU=secondary user.

Operating Assumptions

- PUs' activity: ON/OFF
- Channel: Slowly time varying, Nakagami-m, finite state Markov channel
- Channel scheduling: Max rate

Cross-Layer Design

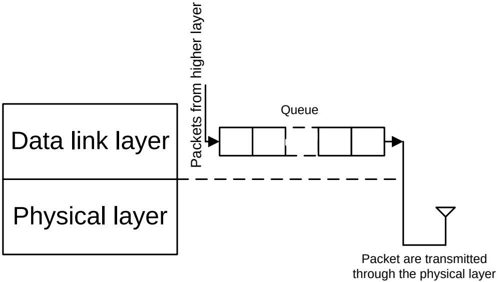


Figure 4: Cross-layer design

- Packet arrival follows batch Bernoulli random process
- Packets are stored in the data link layer's buffer/queue
- Adaptive modulation and coding is employed

Multi-Class Service

- Voice, video streaming and web browsing have stringent delay constraints i.e., delay sensitive (DS) service
- Email has no stringent delay constraint i.e., delay non-sensitive/best-effort (BE) service

Rate Allocation Mechanism for a Particular SU

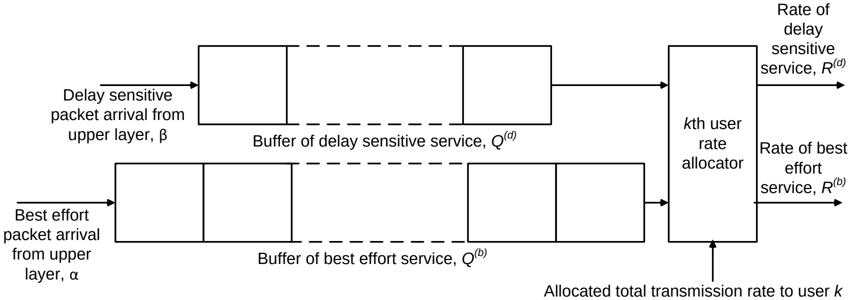


Figure 5: Rate allocation for multi-class service transmission for kth SU.

Optimal Rate Allocation Mechanism

- Formulated the problem as a constrained Markov decision process (MDP)
- Objective

$$\underset{\mathbf{x}(\mathcal{S},\mathcal{A})}{\text{minimize}}[\mathbf{d}^{(d,o)}(\mathcal{S},\mathcal{A})]^{\mathsf{T}}\mathbf{x}(\mathcal{S},\mathcal{A}) \tag{1}$$

$$\text{subject to:}[\mathbf{p}_{\text{loss}}^{(b,o)}(\mathcal{S},\mathcal{A})]^{\mathsf{T}}\mathbf{x}(\mathcal{S},\mathcal{A}) \leq p_{th}^{(b)} \tag{2}$$

$$[\mathbf{p}_{\text{loss}}^{(d,o)}(\mathcal{S},\mathcal{A})]^{\mathsf{T}}\mathbf{x}(\mathcal{S},\mathcal{A}) \leq p_{th}^{(d)} \tag{3}$$

$p_{th}^{(b)}$ and $p_{th}^{(d)}$ are target packet loss probabilities of BE service and DS service, respectively

Optimal Rate Allocation Mechanism

- $\mathbf{x}^*(\mathcal{S}, \mathcal{A})$ denotes the probability of taking action $\mathcal{A}$ in state $\mathcal{S}$ that minimizes the average queuing delay of DS packets while satisfies packet loss probability constraints
- From the optimal values, $\mathbf{x}^*(\mathcal{S}, \mathcal{A})$ one can calculate QoS parameters e.g., packet loss probabilities and queuing delay
- The optimal policies for constrained MDP are random

Suboptimal Rate Allocation Mechanism

if Available transmission rate,
$R \leq$ number of packets in the DS buffer **then**
    $R^{(d)} \leftarrow R$
    $R^{(b)} \leftarrow 0$
else
    $R^{(d)} \leftarrow$ number of packets in the DS buffer
    $R^{(b)} \leftarrow R - R^{(d)}$
end if

Suboptimal Rate Allocation Mechanism

- Developed a queuing analytic model with the suboptimal rate allocation mechanism
- Analyzed queuing analytic model as a quasi-birth-death (QBD) process
- Calculated packet loss probabilities and queuing delay i.e., delay distribution from the steady state probabilities of the QBD

Numerical Results: Cumulative Distribution of Delay of DS Packets

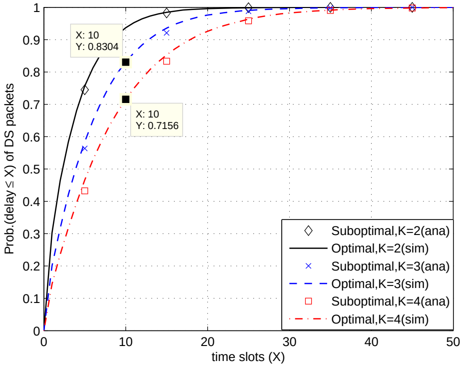


Figure 6: Effect of number of SUs (K) on the delay distribution of DS packets (ana=analysis, sim=simulation)

Numerical Results: Packet Loss Probability of DS service

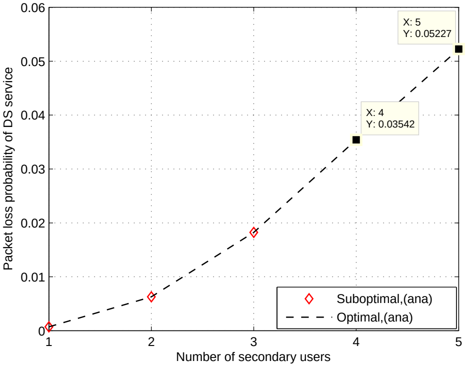


Figure 7: Effect of number of SUs (K) on the packet loss probability of DS service (ana=analysis, sim=simulation)

Numerical Results: Packet Loss Probability of BE service

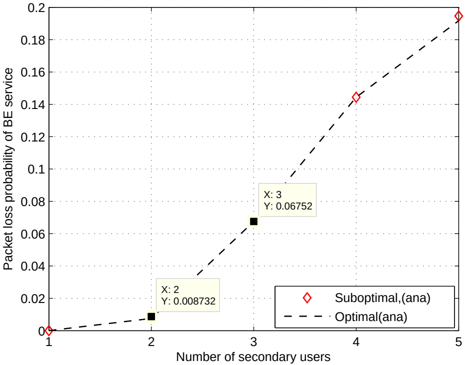


Figure 8: Effect of number of SUs (K) on the packet loss probability of BE service (ana=analysis, sim=simulation)

Application of the Developed Queuing Model with the Suboptimal Mechanism: Example

Table 1: Number of SUs for given QoS requirements ($D^{(d,s)}_{t,max} = 10$ (time slots) with probability=0.8, $P^{(d,s)}_{t,loss} \leq 0.05$ and $P^{(b,s)}_{t,loss} \leq 0.05$)

$K_{D^{(d,s)}_{t,max}}$	$K_{P^{(d,s)}_{t,loss}}$	$K_{P^{(b,s)}_{t,loss}}$	K_s
3	4	2	2

Summary: Part I

- Studied rate allocation mechanisms that allocate rate between two different classes of services of a particular SU
- Formulated the optimal rate allocation mechanism as a MDP
- Also proposed a low-complexity suboptimal rate allocation mechanism
- The performance of the suboptimal rate mechanism is quite similar to the optimal rate allocation mechanism
- Developed queuing analytic model with the suboptimal mechanism is useful not only for calculating QoS parameters but also in making a call admission control decision

Publication

S M Shahrear Tanzil, Md. Jahangir Hossain, and Mohammad M Rashid ,
"Rate allocation mechanisms for multi-class service transmission over cognitive radio networks", accepted in
IEEE Global Commun. Conf. (Globecom'13), Atlanta, USA, Dec. 2013.

Sensing Errors in Cognitive Radio Systems

- Two types of sensing errors i.e., false alarm and miss-detection
- False alarm: CRN may detect a channel being used by PUs where in reality the channel is idle/PUs are not using the channel
- Miss-detection: CRN may not be able to detect an active PU

Random Transmission Protocol

- Traditional deterministic protocol: If the channel is sensed as busy, CR base station (BS) decides to transmit with probability, 0
- False alarm: Sensed as busy but in reality idle
- Random transmission protocol: If the channel is sensed as busy, CR BS decides to transmit with probability, P_1

Random Transmission Protocol

- Traditional deterministic protocol: If the channel is sensed as idle, CR BS decides to transmit with probability, 1
- Miss-detection: Sensed as idle but in reality busy
- Random transmission protocol: If the channel is sensed as idle, CR BS decides to transmit with probability, P_2

Queuing Analytic Model

- Developed a queuing analytic model
- Analyzed the queuing analytic model as a QBD process
- Calculated QoS parameters of SUs e.g., packet loss probability and queuing delay as well as QoS parameters of PUs e.g., collision probability from the steady state probabilities of the QBD

Numerical Results: Packet Loss Probability

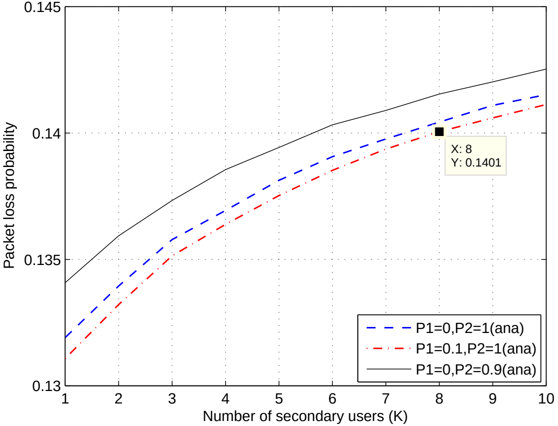


Figure 9: Effect of the values of P_1, P_2 and SUs (K) on the packet loss probability (ana=analysis).

Numerical Results: Average Queuing Delay

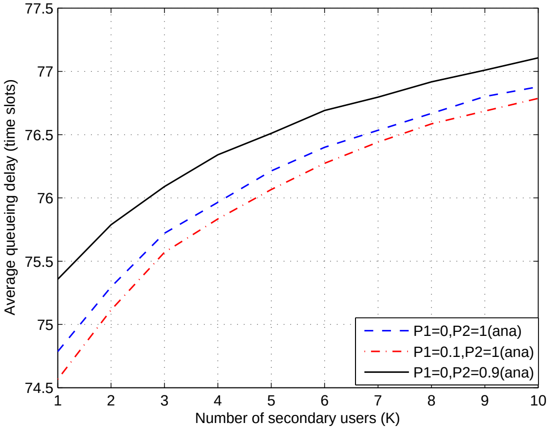


Figure 10: Effect of the values of P_1,P_2 and SUs (K) on average queuing delay (ana=analysis).

Numerical Results: Collision Probability

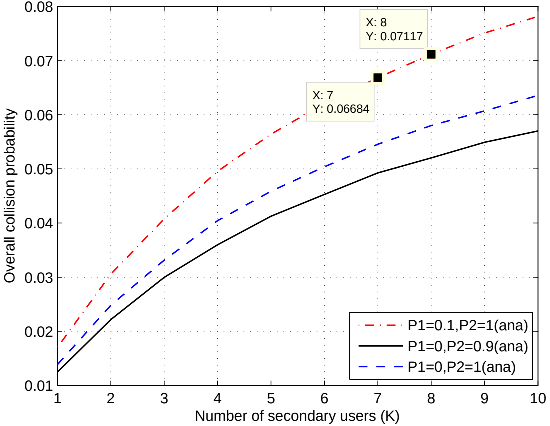


Figure 11: Effect of the values of P_1, P_2 and SUs (K) on the collision probability (ana=analysis).

Application of the Developed Model: Example

Table 2: Transmission Probabilities (P_1, P_2) vs. number of SUs for given QoS requirements ($p_{t,ploss} = 0.14$, $D_{t,avg} = 77$ (time slots) and $p_{t,col} = 0.07$)

(P_1, P_2)	$K_{p_{t,ploss}}$	$K_{D_{t,avg}}$	$K_{p_{t,col}}$	K_s
(0,0.9)	6	9	15	6
(0,1)	7	11	13	7
(0.1,1)	8	12	8	8

Summary: Part II

- Investigated the performance of a random transmission protocol
- Developed a queuing analytic model in presence of sensing errors
- Calculated different QoS parameters using the developed queuing model
- The queuing analytic model is also useful for admission control
- Selected numerical results have shown that random transmission protocol can support more SUs than the classical deterministic transmission protocol

Publication

S M Shahrear Tanzil and Md. Jahangir Hossain,
"Cross-layer performance analysis for cognitive radio network with a random transmission protocol in presence of sensing errors",
in Proc. of *Int. Conf. on Cognitive Radio Oriented Wireless Networks (CROWNCOM'13)*, Washington DC, USA, Jul. 2013.

Thank you!