ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

NEW APPROACHES FOR QUALITY OF SERVICE PROVISIONING IN COGNITIVE RADIO NETWORKS

Ph.D. THESIS

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Department of Computer Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BİLİŞSEL RADYO AĞLARINDA SERVİS KALİTESİNİ YÜKSELTMEYE YÖNELİK YENİ YAKLAŞIMLAR

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Gülnur Selda UYANIK, a Ph.D. student of ITU Graduate School of Science Engineering and Technology, student ID 504112505, successfully defended the thesis entitled "NEW APPROACHES FOR QUALITY OF SERVICE PROVISIONING IN COGNITIVE RADIO NETWORKS", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my spouse,
For all his guidance, his patience and his unending support.

FOREWORD

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Gülnur Selda UYANIK
Computer Engineer, M.Sc.

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ABBREVIATIONS

ACI	**:** Adjacent Channel Interference
AMC	**:** Adaptive Modulation and Coding
BS	**:** Base Station
CBR	**:** Constant Bit Rate
CBS	**:** Cognitive Base Station
CCC	**:** Common Control Channel
CGS	**:** Coarse Grain Scalable
DMOS	**:** Degradation Mean Opinion Score
MGS	**:** Medium Grain Scalable
CR	**:** Cognitive Radio
CRN	**:** Cognitive Radio Network
D-OFDM	**:** Discontinuous Orthogonal Frequency Division Multiplexing
DCP	**:** Data Centric Prioritization
DP	**:** Dynamic Programming
DSA	**:** Dynamic Spectrum Access
FDM	**:** Frequency Division Multiplexing
FoM	**:** Figure of Merit
GB	**:** Guard Band
HP	**:** High Prioritized
GDB	**:** Geo-location Database
GOP	**:** Group of Pictures
ISM	**:** Industrial, Scientific and Medical
ITU	**:** International Telecommunication Union
LTE	**:** Long-Term Evolution
LP	**:** Low Prioritized
MAC	**:** Medium Access Control
MOS	**:** Mean Opinion Score
MSSIM	**:** Mean Structural Similarity
NE	**:** Nash Equilibrium
MPEG	**:** Moving Picture Experts Group
OFDM	**:** Orthogonal Frequency Division Multiplexing
OFDMA	**:** Orthogonal Frequency Division Multiple Access
PU	**:** Primary User
PSNR	**:** Peak Signal to Noise Ratio
RB	**:** Resource Buffer
QoE	**:** Quality of Experience
QoS	**:** Quality of Service
SBS	**:** Secondary Base Station
SSP	**:** Subset Sum Problem
SU	**:** Secondary User
SVC	**:** Scalable Video Coding
TRA	**:** Transmission Rate Adaptation

USRP **:** Universal Software Radio Peripheral

SYMBOLS

$\mathbf{b_f}$	**:** Number of B frames between reference frames.
$\mathbf{c^t}$	**:** PU classification result for a single channel at time instance t.
$\mathbf{c_{\{1,\,2,\,...,\,M\}}{}^t}$	**:** PU classification results vector for M channels at time instance t.
$\mathbf{c_i{}^t}$	**:** PU classification result for channel i at time instance t.
$\mathbf{C_x}$	**:** PU channel numbered x in the multi-channel environment.
$\mathbf{d}$	**:** Data rate demand of an SU.
$\mathbf{D}$	**:** PU traffic mean duty cycle.
$\mathbf{D_{heavy}}$	**:** Duty cycle of a heavily used PU channel.
$\mathbf{D_{sparse}}$	**:** Duty cycle of a sparsely used PU channel.
J:a:b	**:** Chroma sub-sampling method identifiers.
$\mathbf{k}$	**:** Weighting factor of HP packets in FoM calculation.
$\mathbf{M}$	**:** Total number of PU channels in the multi-channel environment.
$\mathbf{M_{heavy}}$	**:** Number of PU channels in *heavy use* in the multi-channel environment.
$\mathbf{M_{sparse}}$	**:** Number of PU channels in *sparse use* in the multi-channel environment.
$\mathbf{M'}$	**:** Number of available PU channels.
$\boldsymbol{\mu}_{\mathbf{OFF}}$	**:** PU Poisson traffic mean for inactive period.
$\boldsymbol{\mu}_{\mathbf{ON}}$	**:** PU Poisson traffic mean for active period.
$\mathbf{N}$	**:** Total number of SUs in the multi-user environment.
$\mathbf{N_{c'}}$	**:** Number of PU channels for each SU to select randomly in random scheduling method.
$\mathbf{N_B}$	**:** Number of B frames in each B packet.
$\mathbf{N_I}$	**:** Number of I frames in each I packet.
$\mathbf{N_L}$	**:** Total number of lost packets for sample setup.
$\mathbf{N_P}$	**:** Number of P frames in each P packet.
$\mathbf{N_T}$	**:** Total number of packets for sample video.
$\boldsymbol{\tau}_{\mathbf{delay}}$	**:** Time-out period for HP SU packets.
$\mathbf{t_s}$	**:** Sampling period of the SUs in the designed CRN model.
$\mathbf{q_{HP}}$	**:** Current queue size for HP packets at a specific SU at time instance t.
$\mathbf{q_{LP}}$	**:** Current queue size for LP packets at a specific SU at time instance t.
$\mathbf{\lvert Q_{HP}\rvert}$	**:** Queue size for HP packets at each SU.
$\mathbf{\lvert Q_{LP}\rvert}$	**:** Queue size for LP packets at each SU.
$\mathbf{R_{heavy}}$	**:** Ratio of PU channels in *heavy use* in the multi-channel environment.
$\mathbf{send_{hp}}$	**:** Binary decision variable/vector for specific SU for sending an HP packet for single/multi-channel environments.
$\mathbf{send_{lp}}$	**:** Binary decision variable/vector for specific SU for sending an LP packet for single/multi-channel environments.
$\mathbf{SU_x}$	**:** SU numbered x in the multi-user environment.
$\mathbf{T_H}$	**:** CBR traffic inter-arrival time for HP packets at sender SUs.
$\mathbf{T_L}$	**:** CBR traffic inter-arrival time for LP packets at sender SUs.
$\mathbf{T_{SIM}}$	**:** Simulation time.

$|W_H|$: Window size for moving average circular buffer at each SU.

x^t : Binary spectrum sensing result for a single channel at time instance *t*.

$x_{\{1, 2, ..., M\}}{}^t$: Binary spectrum sensing results vector for a *M* channels at time instance *t*.

x_{it} : Binary spectrum sensing result for channel *i* at time instance *t*.

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NEW APPROACHES FOR QUALITY OF SERVICE PROVISIONING IN COGNITIVE RADIO NETWORKS

SUMMARY

Along with the proliferation of wireless communication with diverse services and applications, spectrum efficiency has become a major concern in both licensed and unlicensed frequency bands. Cognitive radio networks (CRNs) stand as a solution for meeting the increasing demand on physically limited frequency spectrum by defining the roles of secondary users (SUs) and secondary networks. These users can adopt their radio transmissions with a dynamic and opportunistic manner with respect to the licensed primary users (PUs) using their software controllable and multi-interface transceivers.

Even if the cognitive radio technology defines constrained and secondary networks, along with the increased spectrum demands, the overall network traffic volume and the quality of service (QoS) requirements of associated SUs is expected to increase substantially. In this thesis, encouraged by this forecast, new approaches for QoS provisioning over CRNs are proposed and evaluated.

In the first part of the thesis, detailed in Chapter 3, a channel assignment algorithm is proposed for SUs with traffic demands at heterogeneous QoS classes, that is advantageous over the native schemes. The proposed channel assignment algorithm uses an estimation on the PU activity temporal level in the SU packet selection. The temporal PU activity level is estimated by the distributed SUs that only use their local sensing histories via projecting the moving average value of their individual sensing histories into three temporal activity classes. The devised heuristic cognitive channel selection algorithm is first evaluated for preliminary results for a single SU and a single channel environment. Afterwards, considering a more realistic scenario, multi-channel CRN model is studied. The proposed channel selection method is expanded into a multi-channel case. When the designed model is expanded to have multi-user property, a distributed scheduling mechanism is also proposed to alleviate the problem of managing conflicting interests of distributed and selfish SUs within a single collision domain. The proposed scheduling mechanism is a fast and a distributed scheduling method that only uses a centralized information broadcast upon a topology change (i.e. node addition or removal from the system). Both spectrum assignment and scheduling algorithms were evaluated using MATLAB® models and compared with the native spectrum assignment scheme and random scheduling in several environments. The simulation results show that the proposed method is advantageous in terms of the Figure of Merit (FoM) metric defined by the weighted sum of throughput ratios of the packets successfully reached to the destination. The proposed method, which basically is a fast PU temporal activity level prediction and a channel selection scheme, reflects its advantageous side especially when the spectrum holes belong to a heavily used PU channel.

Later in the second part of the thesis, as a focused case study, MPEG-2 based encoded video transmission problem is studied in Chapter 4 where a distributed and frame-type-differentiated queue management scheme is proposed and evaluated. The proposed queue management method changes the transmit order of the frames in favor of the ones needed by others for them to be decoded and basically decreases the packet loss probability by sending the reference frames first, in order to prevent indirect frame loss due to the decoding dependencies. The discrimination on the packet selection takes place among different video frames within the encoded video burst. The performance of the proposed scheme is investigated with the developed MATLAB® model that is supported by FFmpeg tool for encoding operations. The results validate that the proposed scheme outperformed the native scheme that does not discriminate any internal frame type information among the video packets, in various simulation setups in terms of several video quality metrics, namely: Peak Signal to Noise Ratio (PSNR), Mean Structural SIMilarity metric (MSSIM), and decodable frame ratio (Q).

The contributions of this thesis are the solutions presented for the efficient spectrum management and quality of service provisioning for multimedia traffic transmission in CRNs. Thesis studies cover several CRN models and novel channel assignment and scheduling strategies that are advantageous over native schemes.

BİLİŞSEL RADYO AĞLARINDA SERVİS KALİTESİNİ YÜKSELTMEYE YÖNELİK YENİ YAKLAŞIMLAR

ÖZET

Kablosuz haberleşmenin, çok çeşitli hizmet ve uygulamalar sayesinde oldukça yaygınlaşması ile birlikte, hem lisanslı hem de sertifika veya lisansa gerek olmadan kullanıma açık olan spektrum alanlarının mümkün olan en yüksek verimle kullanılması önemli bir problem olarak ortaya çıkmıştır. Mevcut ağ standardlarında, lisanslanan bir bant, lisans süresi boyunca sadece lisans sahibi tarafından kullanılabilmektedir. Lisanslı bantlarda kullanılan kablosuz haberleşme ağlarının kullanım istatistikleri, uzayda, zamanda ve frekansta yüksek değişkenlik göstermektedir. Amerika Birleşik Devletleri'nin telekomünikasyon otoritesi Federal Communications Commission (FCC) tarafından yapılan ölçümler, lisanslı bantların %90'a varan oranlarda kullanılmadığını göstermiştir. Bilişsel radyo ağları, ikincil kullanıcı ve onların oluşturduğu ikincil ağlar tanımlayarak, doğası gereği kısıtlı bir kaynak olan spektrum alanlarında ortaya çıkan talep artışı problemine bir çözüm olarak ortaya çıkmıştır. Yazılım ile kontrol edilebilen alıcı-verici modülleri sayesinde, bu ikincil kullanıcılar, radyo iletişimlerini, birincil kullanıcıların kullanmadıkları alanları kullanmak şeklinde, fırsatçı ve dinamik bir şekilde yapabilmektedirler.

Kablosuz ve akıllı cihazların çeşit ve kullanım yaygınlığı son yıllarda sürekli artış göstermektedir. Yakın gelecekte ise bu artışın çok daha da büyük oranlar ile olacağı ve haberleşme trafiğinin de paralel olarak artacağı öngörülmektedir. Bu gibi kablosuz teknolojilerin yaygınlaşması, makinelerin ve araçların haberleşmesi, nesnelerin interneti gibi ortaya çıkan pek çok yeni teknoloji ile birlikte, haberleşme kaynaklarının önemi artmakta, bu durum spektrumun giderek kalabalıklaşması sonucunu doğurmaktadır. Artan veri trafiği içerisinde, yapılan pek çok saha çalışmasının da desteklediği üzere, yüksek servis kalitesi gerektiren mobil video gibi trafiklerin oranının artacağı da beklenmektedir. Bilişsel radyo ağları kısıtlı haklara sahip ikincil kullanıcılar için tanımlanmış olmalarına rağmen, giderek artan kablosuz veri trafiği düşünüldüğünde, bu ağlarda da trafik hacminin ve kullanıcıların yüksek servis kalitesi ihtiyaçlarının hızla artış göstereceği tahmin edilmektedir. Bu öngörüler dikkate alınarak, bu tezde, bilişsel radyo ağlarında servis kalitesini yükseltmeye yönelik yeni yaklaşımlar üzerine çalışmalar yapılmış ve önerilen yaklaşımlara ait performans değerlendirmeleri gerçekleştirilmiştir.

Tez çalışmalarının ilk kısmında, trafik istekleri çeşitli servis kalitesi seviyelerinde olan ikincil kullanıcılar göz önüne alınmıştır. Bu kullanıcıların spektrum kullanımları ile ilgili olarak, literatürde yer alan çözümlere göre daha avantajlı olan bir kanal seçme algoritması önerilmiş ve performansı değerlendirilmiştir. Önerilen yöntemde, ilk aşama olarak, spekrum boşluğu belirlenen kanaldaki birincil kullanıcının zamana bağlı trafik davranışı tahmin edilmektedir. Bu tahmin, birincil kullanıcının kullandığı kanalı ne kadar sıklıkta kullandığının bir göstergesi olup, aynı zamanda iki spektrum

boşluğu arasındaki zaman dilimininin uzunluğu hakkında da fikir vermektedir. İkincil kullanıcılar, spektrum algılama modüllerinin çıktısını sürekli olarak kaydederek birincil kullanıcıya ait geçmiş kullanım bilgilerini kendilerinde saklamaktadırlar. Kayan bir ortalama penceresi yardımı ile, ikincil kullanıcılar karar anında pencerede yer alan verilen ortalama değerini üç seviye olarak tanımlanmış sınıflardan birini seçmekte kullanmaktadır. Tahmin edilen birincil kullanıcı zamansal trafik yoğunluğu bilgisi, ikincil kullanıcılar tarafından kanal seçme aşamasında kullanılmaktadır. Önerilen birincil kullanıcı aktivite tahmin yöntemi, dağıtık olarak çalışan ikincil kullanıcıların her biri tarafından bağımsız bir şekilde gerçeklenebilmekte ve ek bir merkez veya komşu kullanıcılar arası kontrol mesajlaşması gerektirmemektedir. Birincil kullanıcı aktivitesi tahmin edildikten sonra çeşitli servis kalitesi seviyelerine ait kuyruklarda beklemekte olan paketlerden uygun olan seçilerek kanal ataması işlemi yapılmaktadır.

Gerçek zamanlı video trafiği gibi örneklendirebileceğimiz yüksek servis kalitesi gerektiren trafik tiplerine ait veri paketleri, alıcı tarafa çok büyük bir gecikme ile ulaştıklarında, son kullanıcı açısından değer kaybetmekte ve herhangi bir pozitif etkiye sebep olmamaktadır. Bu sebeple, bu paketlere belirli bir zaman kısıtı eklenerek, bu zaman kısıtı içerisinde alıcı tarafa ulaşmayan paketlerin sistemdeki kuyruklarda düşürülerek ilerlemeleri engellenmektedir. Önerilen kanal seçiminde faydalanılan temel motivasyon da, birincil kullanıcılar tarafından sıklıkla kullanılan bir spektrum bölgesinde oluşabilecek boşlukların arasındaki aralığın uzun olabileceği, bu sebeple bu kanalın yüksek servis kalitesi gerektiren ikincil kullanıcı trafiği için uygun olmayacağıdır. Bu gözlemin yanı sıra, bahsi geçen birincil kullanıcıların yoğun olarak kullandıkları kanal, düşük servis kalitesi isteği olan, iletim gecikmelerine çok duyarlı olmayan veri istekleri için kullanılarak, bulunan boşlukların yine verimli bir şekilde değerlendirilmesi sağlanabilmektedir.

Önerilen algoritma sezgisel bir yaklaşım olduğu için, ilk performans değerlendirmeleri tek kanal üzerinde ve tek bir ikincil kullanıcı kullanılarak oldukça sade bir bilişsel radyo ağı üzerinde gerçeklenmiştir. Sonrasında, önerilen kanal ve paket seçme algoritması çoklu kanal sistemlerine uygun hale getirilerek, daha gerçekçi bir ağ modeli olan çoklu kanal ve çoklu ikincil kullanıcı modelinde çalışılmaya devam edilmiştir. Bu modelde, kanal seçimlerinin yanı sıra, kendi çıkarlarını gözetmek üzere tasarlanmış olan ikincil kullanıcıların, aynı spektrum olanaklarında spektrumu kullanmak üzere karar alacak olmalarından dolayı oluşabilecek çakışmaları önlemek amacıyla, bir ikincil kullanıcı haberleşme sıralama algoritması tasarlanmıştır. Önerilen sıralama algoritması da kullanılan ağ modeline uygun olarak dağıtık bir yapıda tasarlanmış olup, sisteme yeni bir kullanıcı gelmesi veya sistemden bir kullanıcı ayrılması durumları haricinde, merkezi bir bilgi alışverişine ihtiyaç duymamaktadır.

Önerilen yöntemlere ilişkin olarak, gerekli sistem birleşenleri MATLAB® ortamında modellenmiş olup, çok çeşitli ağ paramatreleri ile performans değerlendirmeleri yapılmıştır. Önerilen yöntemlerin, referans yöntemlerle karşılaştırıldığında daha yüksek performansa sahip olduğu görülmüştür. Kullanılan başarım ölçütü ise, çeşitli servis kalitesi seviyelerindeki paketlerin alıcı kullanıcıya ulaşma oranlarının ağırlıklı toplamı olarak tanımlanmıştır. Kullanılan modelde spektrum boşlukları hatasız bir şekilde algılanabildiği ve önerilen sıralama algoritması ikincil kullanıcılar arasındaki çakışmaları tamamiyle engellediği için, spektrum bosluklarının hepsi efektif olarak

kullanılabilmektedir. Kullanılan boşlukların, alıcı açısından daha değerli paketler için kullanılıp kullanılmadığı bilgisi ise bu tanımlanan metrik ile yansıtılmaktadır.

Tezin bu kısmında önerilen yöntemler, karmaşıklığı düşük, dağıtık bir şekilde gerçeklenebilir ve geleneksel yönteme göre denk veya bazı koşullarda daha iyi olan bir performansa sahip olan spektrum karar ve paylaşım yöntemleridir.

Tez çalışmalarının ikinci kısmında, bilişsel ağlarda ikincil kullanıcılara servis kalitesi sağlamaya yönelik çalışmalar kapsamında özel bir trafik tipi olan video transferi konusuna yoğunlaşılmıştır. Bu bağlamda, MPEG-2 tabanlı kodlama kullanılan video transferi örnek problem olarak ele alınmış, dağıtık ve çerçeve tiplerini ele alan bir kuyruklama yöntemi önerilmiş ve değerlendirilmiştir. Önerilen kuyruklama yönteminde katkıda bulunulan kısım, veri paketlerinin iletim kuyruğuna yerleştirilmesi aşaması olup, bu yöntem ile daha önemli paketlerin kuyrukta daha önde yer almaları sağlanmıştır. Önerilen yöntemdeki temel fikir, kuyrukta daha önde yer alan bu paketlerin bekleme zamanlarının belirli bir değeri aşması sebebi ile düşürülmesi olasılıklarının diğer paketlere oranla azaltılmış olmasıdır. Böylelikle, çeşitli ağ durumları sebebi ile paket kaybnını önlenemediği sistemlerde, düşen paketlerin, yüksek önemli paketler yerine daha az önemli olan paketlerden oluşması sağlanmıştır. Sistemdeki paketlerin değişiklik gösteren önemleri ise taşıdıkları çerçevelerin uygulanan kodlama yöntemindeki görevleri ile ilgli olarak tanımlanmıştır. Kod çözme aşamasında diğer çerçevelerin çözülmeleri için alıcı tarafa ulaşması gereken referans çerçevelere ait paketler yüksek önemli paketler iken, paket kaybına uğradıklarında kendilerinden başka paketin kod çözme aşamasında herhangi bir zararına sebep olmayacak paketler ise en az önemli paketler olarak tanımlanmıştır.

MPEG-2 kodlama yönteminde, paketlere önem açısından bakıldığında, I, P ve B tipi çerçeveler taşıyan paketler, sırasıyla, en çok, orta ve en az önemli paketler olarak değerlendirilmiştir. Kısaca tanımlandığında, bu kodlama yönteminde, kodlanmış video karelerine ilişkin olarak, en az sıkıştırma oranına sahip I çerçeveleri, sadece ilgili video karesine bağlı olarak kodlandıklarından, başka çerçevelere ihtiyaç duymadan alıcı tarafında çözülebilmektedir. P tipi çerçeveler ise, ilgili video karesine ek olarak, kendilerinden önceki I ya da P tipi çerçevelere de bağlı olarak tanımlanmaktadır. P çerçeveleri, I ya da P çerçevelerine göre oluşan farklılıkları kodladıkları için, daha yüksek sıkıştırma avantajına sahip olmakla birlikte, alıcı tarafta çözülebilmeleri için, kullandıkları I ya da P çerçevesinin de alıcı tarafa ulaşmasını gerektirmektedir. Daha da yüksek sıkıştırma oranları elde edebilmek üzere, hem kendinden önceki hem de kendinden sonraki çerçevelere refrans verebilen, çift yönlü fark bilgisi içerebilen B tipi çerçeveler ise boyut olarak en küçük çerçeve olmaları avantajlarına sahiptir. Buna karşın, alıcı tarafta çözülebilmeleri için, P tipine benzer şekilde, referans olarak kullandıkları her iki çerçevenin de alıcıya erişmiş olmasını gerektirmektedirler. Bu nedenle, I çerçevelerinin kaybolması bağımlı P ve B çerçevelerinin de kaybına sebep olabileceğinden, bu çerçeveler en önemli, P çerçevelerinin kaybolması benzer şekilde B çerçevelerinin çözülmesine engel olabileceğinden orta önemli, B çerçevelerinin kaybolması ise tekil bir kayıba sebep olacağı için bu çerçeveler en az önemli olarak değerlendirilmiştir.

Tezin ikinci kısmında önerilen yöntem, tasarlanan MATLAB® modeli ile simule edilmiştir. Bu modele destek olarak, video kodlama ve kod çözme aşamalarında ise FFmpeg programından faydalanılmıştır. Çeşitli görsel video kalite metrikleri açısından, önerilen yöntemin geleneksel yönteme oranla daha başarılı olduğu

gösterilmiştir. Geleneksel yöntem olarak bahsi geçen yöntemde, paketler içerdikleri çerçevelerin tipine bağlı olmaksızın, haberleşme kuyruğuna çerçeve sıraları ile yerleştirilmektedir. Bu sebeple, bu yöntemde, veri kayıplarının dağılımı üzerinde herhangi bir etki olmamakta, önerilen yönteme göre daha fazla miktarda kayıplar yaşanabilmektedir. Kullanılan perfromans ölçütleri, pek çok referans çalışmada da kullanılmakta olan, Tepe İşaret Gürültü Oranı (PSNR), Ortalama Yapısal Benzerlik Oranı (MSSIM) ve çözülebilen çerçeve oranı (Q) şeklindedir.

1. INTRODUCTION

The pervasion of the mobile devices over recent decades has significantly increased the preference of wireless communication. Consequently, the spectrum map is getting crowded to a greater extent, encouraging the researchers to work on efficient use of this now valuable resource. Cognitive radio (CR) is a communication paradigm that tries to circumvent the inefficiencies of the traditional communication standards. Cognitive radio network (CRN) devices try to opportunistically utilize all spectrum vacancies rather than communicating at a certain and reserved spectrum portion [7].

This thesis focuses on both efficient spectrum management of wireless communication through CR principles and quality of service provisioning for multimedia traffic transmission, which is another key concern of this era. In Section 1.1, the basics of CR technology is presented. The contributions of this thesis are outlined in Section 1.2, that is followed by the organization of the dissertation in Section 1.3.

1.1 Cognitive Radio Networks

The continuous emerge of new wireless technologies and a variety of small scale devices has significantly increased the demand for broader radio frequency spectrum, resulting in over-crowded unlicensed frequency bands (e.g., ISM bands). On the other hand, several field studies have shown that the licensed bands are vastly underutilized [8].

Motivated by the need for more efficient utilization of the licensed spectrum and facilitated by recent regulatory policies, significant research has been conducted towards developing CR technologies for dynamic spectrum access (DSA) networks. CR devices utilize the available spectrum in a dynamic and an opportunistic fashion without interfering with the co-located primary users (PUs). The communicating entities of an opportunistic CRN are called secondary users (SUs). As demonstrated in Figure 1.1, the spectrum opportunities may vary in both frequency and time domains.

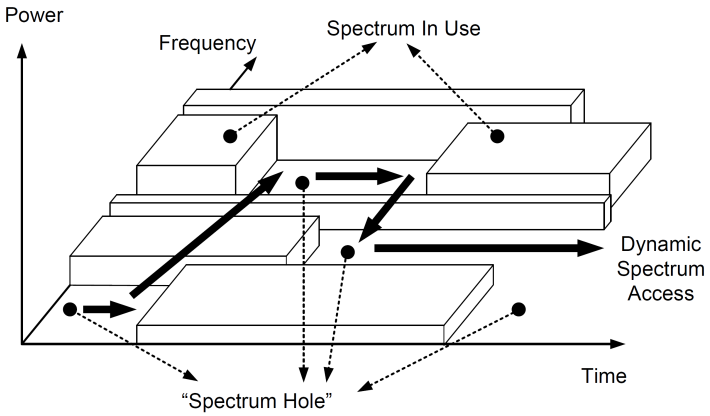


Figure 1.1 : Spectrum opportunities in time and frequency domains [2].

Along with the licensed spectrum bands, the primary network can also reside upon the unlicensed bands. In the meantime, to support the applications with high rate demands, the IEEE 802.11n and the IEEE 802.11ac standards have adopted channel bonding [9], which refers to the bundling of multiple adjacent channels that can then be treated as a single block with a data rate that is approximately the sum of the data rates of the contributing channels. This concept can be extended to non-adjacent frequency channels, that is referred as channel aggregation. These two concepts are very motivating for the employment of CR spectrum management techniques that usually inherit channel aggregation and bonding intuitively.

CR technology and its paradigm has brought up many new operating challenges in all network layers. The four fundamental functionalities of the spectrum management in CR networks are as follows: *Spectrum Sensing*, *Spectrum Management/Decision*, *Spectrum Sharing* and *Spectrum Mobility* [2]. In this thesis, solutions for both spectrum decision and spectrum sharing functionalities are presented.

CR principles are designed to be employed in several modern networks like Vehicular Networks [10], Smart Grid Networks [11] and femtocell networks [12], enabling expansion of any spectrum management research over these promising areas. IEEE 802.22 is the very first standard that employs CR techniques over a wireless spectrum. This standard is suited for a cognitive enabled wireless regional area network using whitespaces in the spectrum band of TV signals at 54 to 862 MHz [13].

The motivation of this thesis of this thesis is that the quality of service (QoS) demanding traffic types, like mobile video traffic, will pervade so drastically that

the CRNs will eventually be used to offload these traffic from the primary network. Encouraging this motivation, the white paper from Cisco: *"VNI, Global Mobile Data Traffic Forecast Update, 2016-2021"* [3] includes the claim: "Over three-fourths (78 percent) of the world's mobile data traffic will be video by 2021". This growth phenomenon is also visualized in Figure 1.2 where a very high increase in the percentage of video traffic -which is already at 60%- is expected. Therefore, even if the CRNs consist of SUs that have no predetermined privileges, they will still have to support the transmission of high QoS demanding traffic types. It also has to be noted that QoS-aware spectrum decision/assignment schemes must also consider the trade-off between overall fairness among the CR users and a better spectrum utilization.

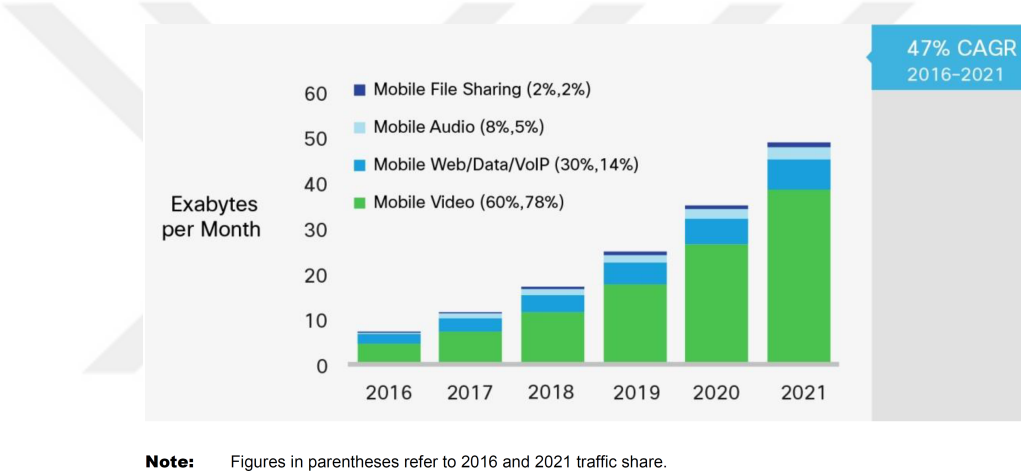


Figure 1.2 : Projections on the distribution of the mobile data traffic [3].

1.2 Contributions of Dissertation

Considering the widespread wireless technologies and increasing demand for multimedia transmission, the studies presented in this thesis are focused on providing QoS in secondary networks, particularly efficient channel assignment for QoS demanding services in CRNs. Moreover, scheduling solutions are also presented among contending SUs for enabling deployments in multi-channel and multi-user environments. A specific case study is also performed with MPEG-2 encoded video transmission over CRNs, for which a frame-type-differentiated queue management scheme is proposed.

The main contributions of this thesis can be listed as:

- A channel assignment algorithm is proposed that couples an estimation of the PU activity level with the SU packet selection among different QoS levels upon a spectrum hole opportunity. The proposed cognitive channel selection method is developed first, considering a simplified network having a single channel and its performance is investigated. Secondly, considering a multi-channel environment, to alleviate the problem of managing conflicting interests of distributed and selfish SUs within a single collision domain, a distributed scheduling mechanism is proposed. Coupled with the spectrum assignment scheme, the proposed mechanisms were designed to be well suited for multi-channel and multi-user environments employing multi-interface capable SUs.

  Several network models and topologies are designed in detail using MATLAB® and MATLAB Simulink® that is used in the evaluation of proposed methods.

  The extensive simulations validate the effectiveness of the proposed channel assignment scheme in terms of a *Figure of Merit*, in this thesis, that is defined as the weighted sum of the throughput ratio values for packets of different QoS levels. The results also show the performance of the proposed scheme is better with respect to a native scheme that utilizes every spectrum opportunity in favor of the most demanding traffic flow.

- A queue management scheme is proposed for the arrangement of MPEG-2 encoded video frames for a burst type video transmission request in a multi-channel CRN environment. The proposed scheme uses the frame type information inside the video packets to be transmitted, and provides a more intelligent protection for a probable packet loss that results from the dynamic nature of the SU spectrum availability. Firstly, the motivations behind the proposed scheme are presented and verified. Then its performance is evaluated via several simulations using designed MATLAB Simulink® model and FFmpeg tool. The results validate performance gain in several video quality metrics, namely: Peak Signal to Noise Ratio (*PSNR*), Mean Structural SIMilarity metric (*MSSIM*), and decodable frame ratio (*Q*), with respect to a native scheme that does not discriminate any internal frame type information among the video packets.

- Other studies performed related to the thesis include: a method for efficient incorporation of the guard-bands into the spectrum scheduling to account for adjacent channel interference for single-link and multiple link cases, an implementation of a CRN testbed using universal software radio peripheral (USRP) modules, and a heuristic prediction methodology of the primary user activity based on history windowing.

1.3 Organization of Dissertation

The rest of the thesis is organized as follows:

Chapter 2 contains previous studies in the scope of this thesis.

New channel selection and scheduling methods are presented in Chapter 3. The proposed channel assignment algorithm, briefly, incorporates PU temporal activity level estimation into the SU packet selection that accounts for different QoS levels. Chapter 3 is divided into two main sub-sections to include developed methods for single and multi-channel environments. The proposed methods are presented in these sections in detail, along with the development of the network model and the performance measurement results with respect to the native methods that reflects the proposed methods outperformed the native ones. The second sub-section includes the modification of the proposed solutions for a multi-channel and a multi-user environment. Thus, in addition to a channel selection algorithm, an SU scheduling method is also proposed, presented and evaluated.

In Chapter 4, a distributed queue management scheme for video transmission over CRNs is proposed and evaluated. The proposed method uses the frame type information inside the video packets, and provides a smart protection against a probable packet loss that results from the dynamic nature of the SU spectrum availability. The detailed information about the design of the proposed mechanisms, the employed CRN model and the obtained results from the performance evaluations are also presented in Chapter 4.

The thesis is concluded in Chapter 5 by summarizing the achievements and giving future directions.

2. RELATED WORK

In this chapter, cognitive radio networks related reference studies are organized under the following subsections: Section 2.1 includes the spectrum decision functionality related works, Section 2.3 includes the quality of service provisioning works and video transfer related works are given under Section 2.4.

2.1 Spectrum Decision in Cognitive Radio Networks

Spectrum decision is an important functionality of CRNs that directly effects the overall network performance of secondary users. The spectrum decision functionality concerns about the *decision* of a channel status on whether a PU is transmitting or not. The spectrum decision methods utilize simultaneous channel monitoring and instantaneous sensing decisions.

Usually, the spectrum decision algorithms work through a decision cycle and produces results for a transmission cycle that comes afterwards. In [14], the authors have proposed different spectrum prediction and decision schemes that aim to provide a fast and an accurate prediction on the spectrum usages of the PUs with the help of a history window, consisting of previous spectrum decision results. The proposed methods are based on the correlation and linear regression analysis of the previous decisions, aiming to further forecast the future spectrum status. In [14], the effective transmission times are increased for SUs as the SUs start transmission without waiting the current sensing cycle's result whenever the prediction result reflects a spectrum opportunity. This increase in the transmission capacity comes with a trade-off between increased probability of PU disturbance and the throughput gain. Simulation results in [14] showed that among the proposed prediction schemes, the correlation based spectrum prediction scheme increases the system utility while providing a lower PU disturbance ratio. In this thesis, proposed methods also benefit from the individual spectrum sensing histories but do not forecast a sensing decision, instead, use this

information for the classification of PU temporal status to assist spectrum selection algorithms.

The monitoring network concept is introduced in [15], in which each monitoring node performs an auto-regression analysis of first degree in order to model the monitored signal. After collecting the monitoring coefficients from the monitoring nodes, the centralized module estimates transmission signal for each PU channel in a more robust manner and classifies the PU channels in three classes as: busy, moderate and idle. The authors defined three classes in terms of QoS demands as: VoIP users, video-streaming users and best effort users and mapped these levels to classified channels. In this thesis, PU activity is classified in similar classes but the classification is performed distributively at each SU and derived from the history perceived. A uniformly weighted mean of the samples in the history window of a specific SU is utilized instead of a group of spectrum samplings gathered from the monitoring nodes.

Most commonly used spectrum sensing method is the energy-detection. Therefore, this method is implemented in many of the test bed studies which have many intrinsic challenges. Yan et al. implemented one of the very first CRN test beds based on universal software radio peripheral (USRP) nodes using energy detection for spectrum sensing and orthogonal frequency division multiplexing (OFDM) implementation with five channels [16]. [4] is another test bed study, extending existing works by further including performance analysis on varying network parameters like the environmental noise level and the PU traffic intensity. In [4], the test bed environment is presented using USRP devices and LabVIEW® development environment. The presented test bed environment and the USRP based SU nodes can be seen in Figure 2.1 and Figure 2.2, including a single PU, a single SU with the sensing and transmission modules and a signal noise generator for injecting a controllable amount of noise.

USRP devices are software-programmable radio transceivers providing software-reconfigurable RF platforms. Therefore, these devices are very fitted for software defined radio and CRN test bed realizations. Several experiments were conducted in [4], related to spectrum sensing based on energy detection principle as well as the dynamic spectrum access behavior of the SU node. In the network model employed in [4], there exists a single PU working on a predetermined channel. A single SU embraces dynamic spectrum access principles, that is, it learns about

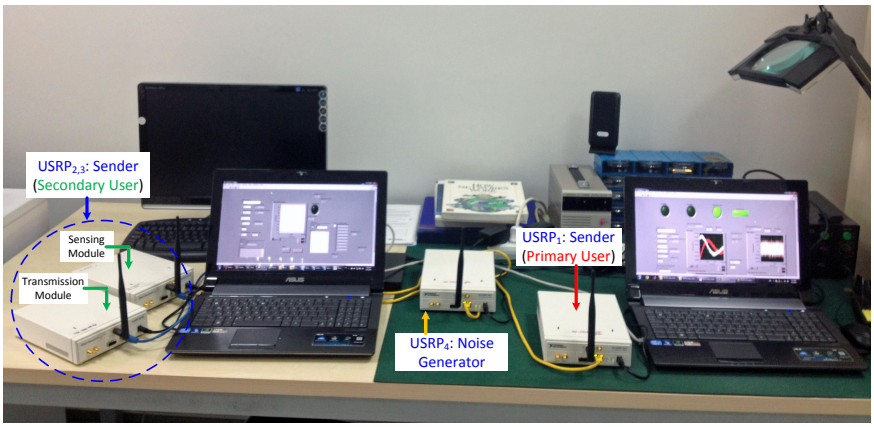


Figure 2.1 : Dynamic spectrum access test bed using USRP devices [4].

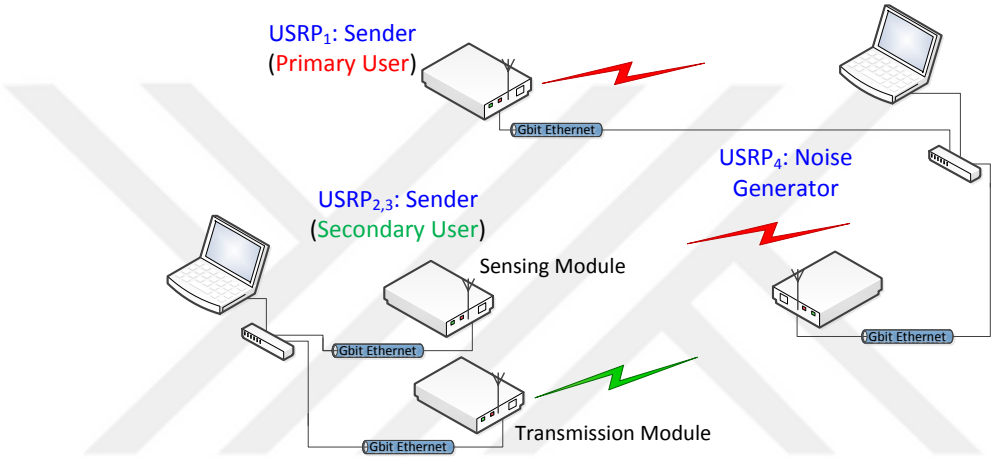


Figure 2.2 : Dynamic spectrum access test bed system model [4].

the channel status with the help of its sensing module and utilizes the spectrum opportunistically based on the vacancy of the PU via its transmission module. A parallel spectrum sensing approach, that is similar to the one in [17], is employed such that, for an SU device, a *separate spectrum sensing module* works in parallel with the *transmission module* which is responsible for the data transmission on the discovered spectrum holes. Similar parallel sensing approach is also employed in the studies presented in this thesis in the latter sections. Several experiments were performed in [4] related to the dynamic spectrum access behavior of an SU node under the scenario where the PU node is generating Poisson traffic pattern with varying traffic rate parameters. As seen in Figure 2.2, a controllable noise generator node is also used to investigate the effect of the environmental noise on energy-detection-based spectrum sensing algorithm. The experiments supported expected performance behaviors such that performance of the energy-detection-based spectrum sensing

algorithm highly decreases as the noise in the environment increases and increasing PU activity decreases SU throughput. This test bed environment can be used as a basis for multi-hop, multi-channel cognitive radio test bed environments.

2.2 Spectrum Sharing in Cognitive Radio Networks

After the spectrum sensing and decision processes, detected or predicted spectrum holes need to be utilized by the CR users conforming to specific principles. In CRNs, SUs do not tend to have an intrinsic priority or scheduling over the neighboring contending SUs by design. There is a vast research in scope of *spectrum sharing* algorithms and MAC protocols to solve the scheduling problem among these users to improve overall spectrum utility and prevent the collision on the same spectrum holes that are detected by multiple SUs subjected to the same PU traffic.

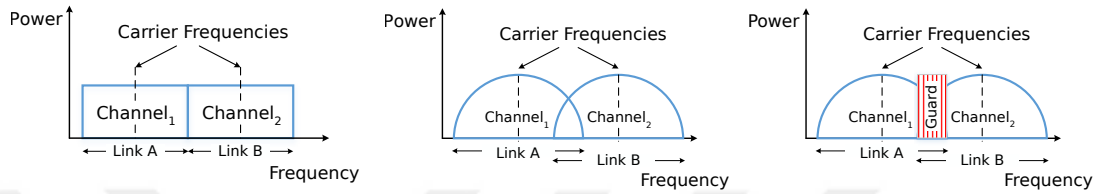
The spectrum sharing mechanisms distribute spectrum opportunities among secondary users who can be treated as having equal rights because none of them have any license or payment right on the spectrum. The classification of the spectrum sharing algorithms are defined as:

- **architecture-based:** *centralized* (e.g. spectrum server approach and auction based schemes) or *distributed* (e.g. local bargaining)
- **spectrum allocation behavior based:** *cooperative* (CR users help each other and share their observations) or *non-cooperative*
- **spectrum access technique based:** *overlay* (access spectrum if no PU exists) or *underlay* (PU/s exist but CR users access to spectrum in a way that their disturbance does not exceed a threshold).

In this thesis, the proposed spectrum sharing method, presented in Section 3.2.3, is an example of a distributed, non-cooperative and an overlay spectrum sharing algorithm.

Along with the hardware advances, SUs tend to be capable of using multiple channels in parallel. Hence, the spectrum contention among SUs may be on multiple channels as well as on a single channel necessitating the spectrum sharing algorithms being able to handle both single and multi-channel assignment of individual SUs. Moreover, several practical challenges may couple into spectrum sharing algorithms like adjacent

channel interference (ACI) [5]. Spectrum sharing, and more generally, channel assignment mechanisms in multi-channel wireless networks are often designed without accounting for ACI. ACI is a form of power leakage from adjacent channels, attributed to non-idealities of filters, amplifiers and clock sources in the RF transmitters. To prevent such interference between different users in a network, guard-bands (GBs) are needed. Figure 2.3 visualizes the adjacent-channel interference and the placement of a GB among adjacent transmission channels.



(a) Ideal power spectral density. (b) Power spectral density in a practical communication system. (c) Power spectral density under the "GB reuse" model.

Figure 2.3 : GB aware channel assignment [5].

Introducing GBs has a significant impact on spectrum efficiency. In [4], the authors studied two models for utilizing GBs in a dynamic spectrum access network: "GB reuse" and "no GB reuse". According to the "GB reuse" model, GBs can be shared by two different (interfering) links. In contrast, in the "no GB reuse" model, two adjacent transmissions require their own GBs. As explained in [18], the "GB reuse" model is suitable for discontinuous-orthogonal frequency division multiplexing (D-OFDM)-based systems, whereas the "no GB reuse" model is suitable for FDM-based systems.

Recently in [19], distributed channel aggregation was studied within a framework using the game-theory. The authors modeled the problem of distributed channel selection with aggregation as a stochastic game with incomplete information. They have shown that by adopting learning automata, the radios converge to a Nash equilibrium. A spatial spectrum sharing-based channel aggregation was studied in [20] from a game-theory perspective. In [20] , the authors considered a model where an operator can access and aggregate the licensed spectrum of other operators upon payment of a certain fee. They modeled the channel aggregation problem as a pricing game. Then they related the pricing game to a power control game, and derived the Stackelberg equilibrium for the pricing and power optimization problem. In [21], the problem

of dynamic inter-network channel aggregation was studied, where mobile operators decide whether to allow a portion of their spectrum to be used by other operators for a given duration. They modeled the problem as a Bayesian game with incomplete information. A distributed algorithm that approaches a neighborhood of a Bayesian Nash equilibrium was proposed. Although co-channel interference was extensively studied in the context of distributed channel allocation (e.g., [22], [23]), most existing works on channel allocation, including the schemes that support channel aggregation, do not account for ACI.

In [4], the authors presented a channel assignment mechanism that aims at maximizing the spectrum efficiency. More specifically, this mechanism attempts to minimize the amount of additional GB-related spectrum that is needed to accommodate a new link. Inline with the IEEE 802.11n (by bonding two 20-MHz channels, IEEE 802.11n supports a single 40 MHz channel) and the IEEE 802.11ac standards, the proposed assignment mechanisms support *channel bonding*, and more generally, *channel aggregation*. Channel bonding refers to the bundling of multiple adjacent channels, which can then be treated as a single block whose data rate is approximately the sum of the data rates of the individual channels. This concept can be extended to non-adjacent frequency channels, and is referred to as channel aggregation. LTE-Advanced supports channel aggregation for 4G cellular networks by allowing mobile operators to aggregate spectrum from non-adjacent bands to support links with high demands [24].

The optimal ACI-aware channel assignment for "GB reuse" model is formulated in [4] that maximizes the spectrum efficiency, while supporting channel bonding and aggregation, as a subset-sum problem (SSP). An exact exponential-time dynamic programming (DP) algorithm, a polynomial-time greedy heuristic, and an ε-approximation are proposed and compared. Results reveal a considerable improvement in spectrum efficiency achieved by the proposed algorithms compared to the recent work in the literature. For the spectrum status in Figure 2.4, each set of consecutive idle channels can be grouped into an "idle frequency block", as illustrated in Figure 2.5 as "GB reuse" model is employed.

Channel assignment of an SU can result with no additional GB introduction to existing channel conditions when the demand of the SU can be met as an exact sum of the

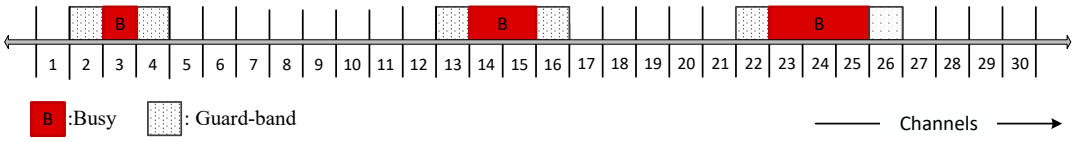


Figure 2.4 : Spectrum status (channel assignment) at a given time instance [4].

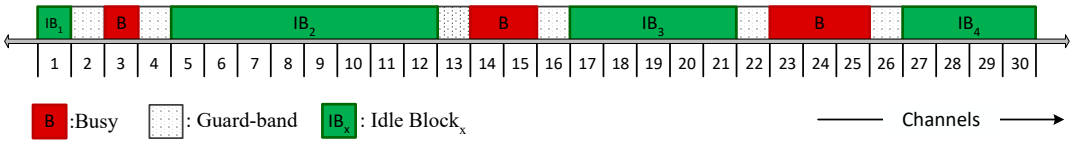


Figure 2.5 : Set of idle blocks for the spectrum map in Figure 2.4 [4].

some combination of existing idle blocks. Example demand and how it is met by using existing idle blocks can be seen in Figure 2.6. Each channel in the demonstration has 1 Mbps bandwidth. As the example data demand is 6 Mbps and the sum of the capacities of the first idle block (IB_1) and the third idle block (IB_3) is 6 Mbps, the demand is met with these two, resulting in no additional GB.

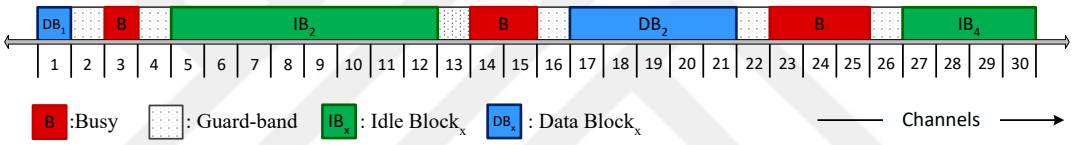


Figure 2.6 : Channel assignment with no additional GBs ($d = 6$ Mbps) [4].

When the traffic demand is not an exact sum of any combination of existing idle blocks, some of the idle blocks has to be separated, and a single additional GB is introduced to the system (see Figure 2.7, where demand is 7 Mbps and met with idle blocks 1 and 3, supported by a part of idle block 4). As assigning a channel as a GB decreases the SU throughput, the number of total GBs are intended to be minimized for maximum achievable SU throughput. The authors in [4] provided proof of when augmented with the proposed post-processing phase, SSP attains the optimal GB aware channel assignment that achieves the maximum spectrum efficiency.

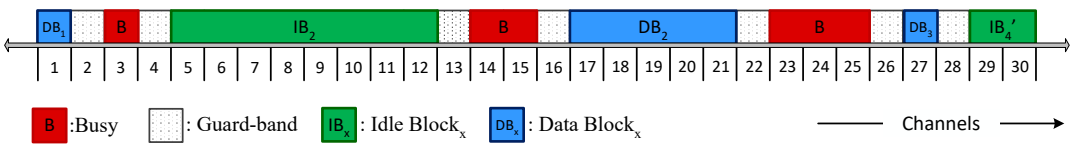


Figure 2.7 : Channel assignment with one additional GB ($d = 7$ Mbps) [4].

In [5], the authors extended previous work [4] for capturing problem of the spectrum assignment of multiple SUs. Both single link (sequential) as well as multiple links

(batch) assignments were considered. For a single link, the optimal assignment problem was formulated as an SSP like in [4], and exact and approximate solutions were presented. Afterwards, considering a set of links (batch assignment), the optimal ACI-aware exponential-time assignment is formulated that maximizes the network's spectrum efficiency. To avoid the high complexity of the exact multi-link assignment algorithm, a polynomial-time sequential assignment was presented, which adopts a greedy strategy for each link. The numerical results presented showed that the greedy sequential assignment achieves a near-optimal performance and outperforms solutions in the referenced related work.

2.3 Quality of Service Provisioning in Cognitive Radio Networks

Providing a certain level of QoS to the SUs is a very challenging problem as these users are strictly constrained by the PU arrivals. In [25], where the multimedia routing and the spectrum assignment problems in CR sensor networks are researched, the authors also coupled the energy level information of the nodes. The number of clusters used is determined optimally according to the packet loss and latency metrics. After clusters are determined, the channel allocation scheme in the cluster is employed by the cluster head based on ascending order of delay budget of SUs. In the network models used throughout this thesis study, different queues are employed for different traffic types at each SU and not only a delay-sensitive but more of a heterogeneous traffic is served.

Previously mentioned reference work [25] also covers the related works on multimedia transmission in CRNs. There exists many studies including auction based schemes, centralized optimizations and intra-frame refreshing rate adaptations based on sensed channel conditions. As the authors also noted, most of the recent work focuses on finding the best channel for the multimedia traffic and mostly centralized approaches were proposed. QoS is mostly handled in terms of the number of assigned channels and a principle of assigning more channels to high prioritized traffic level is adopted like in reference works [26] and [27]. In this thesis studies, it is shown that this approach does not necessarily provide the best performance in terms of overall utilization when SUs have mixed traffic on different QoS levels and different levels of PU temporal activity.

Most of the QoS works emphasize on the delay considerations of SUs. The work in [28] also considers delay sensitiveness. The authors propose a cognitive radio resource

management scheme in which they analytically derive the effective capacity, the optimum sensing period and radio resource allocation while statistically guaranteeing the QoS of the femtocell.

Delay sensitive and best effort traffic types are also defined and used in [29], where the authors proposed priority queuing model and presented Markov decision processes for which a reinforcement learning is applied to find the optimal solutions. Multiple on-off servers and two types of queues for each SU are inserted into the developed model and centralized load balancing entity handles queue theoretic load balancing operations. Channel status and queue length information are fed back to the load balancer, which then performs delay minimization through devised reinforcement learning strategy.

Spectrum sharing works may also couple QoS concerns on spectrum band decisions. In [30], spectrum sharing in terms of power allocation problem is implemented as a non-cooperative game in which each user selfishly aims to achieve its target QoS using as little power consumption as possible. A distributed algorithm to find the Nash Equilibrium (NE) is presented [30]. The problem of spectrum allocation for carrier aggregation in small cell CRNs is also formulated as a Quality of Experience (QoE)-aware game model in [31]. Modeled game was an exact game and a multiple players carrier aggregation learning algorithm is proposed based on stochastic learning automata, that is proved to converge towards NE. The authors defined utility functions of SUs for two different types of QoS classes like multimedia traffic and elastic traffic that resembles best-effort type. Like multiple-channel studies in this thesis, every SU in [31] has the ability to aggregate multiple channels.

Wiggins et al. proposed in [32] a method that they call Data Centric Prioritization (DCP) in which they try to determine an application's QoS requirements and choose the best frequency for each SU accordingly. They try to rank the available frequencies considering the applications' delay, jitter, loss and bandwidth sensitivities and they assign some priorities accordingly. Basically, they try to capture the spectrum hole which is the best fit for the applications need. Their research enables a prioritization of the frequency spectrum. However, DCP does not mandate the order of usage. Moreover it needs to analyze the physical properties of the spectrum band in order to calculate QoS metrics.

The centralized solutions, like the graph coloring analogy work in [33], can benefit from the optimization problem development, as well as the declaration of variety of utility functions and constrains using a centralized entity. In [26], another graph coloring based channel allocation is proposed considering both fairness and QoS requirements of CRNs, that works within a distributed manner. The authors defined four traffic classes and managed spectrum sharing accordingly. The QoS metric used in that reference work, is the weighted average of the number of different packets sent/received in the last ten frames. In this thesis, a more realistic figure of merit is defined that is presented further in detail in Section 3.

Studies in [27] include a centralized solution as well, where the authors employed a queuing theory based approach to formulate the number of channels to be aggregated. Previously mentioned reference works include multi-channel spectrum utilization at each SU (a.k.a. multi-interface usage) whereas for some practical environments, SUs may be limited to use single channel, like in [34]. In this thesis, methods for both single-channel and multi-channel environments are presented. The authors in [34] achieved to outperform well-known reinforcement learning algorithms by proposing an online learning policy for distributed SUs, that takes into account not only the availability criterion of a band but also a quality metric linked to the interference power on sensed band.

As it can be seen from these works that covers QoS implementations on secondary networks, guaranteeing or evaluating closed form expressions of QoS requirements requires complex processing of the communication parameters even for a centralized entity. In this thesis, a simple, fast, and distributed scheduling mechanism is developed for SUs to achieve a collision-free scheduling among SUs to assist the proposed QoS sensitive spectrum assignment algorithm. The probable drawbacks of this simple implementation and the counter solutions are discussed in latter sections.

Even if the majority of the existing studies benefit from the centralized solutions, a distributed solution may be more preferable due to the dynamic and ad-hoc nature of CRNs. However, a distributed solution may suffer from common control channel (CCC) deficiencies if it utilizes extensive messaging like the work in [26] in which channel availability lists and the resource share values of the nodes are exchanged

through the CCC among the SUs. In this thesis, the CCC connection is highly limited to an occasional access by the SUs.

In [35], the authors proposed a distributed matching algorithm that exploits the channel state information of the vacant channels to handle QoS-constrained spectrum access. They also proposed a fast version of the proposed matching algorithms. Considered QoS requirements of the SUs are given as average data rate, delay and packet error rate. The drawback of their proposed scheme is that it necessitates the PU to act like a centralized entity among contending SUs nearby. In reality, superior PU users may not accept to take CRN related responsibilities. Moreover, as the authors also noted, for the achievement of a better solution, extensive messaging may occur in their described distributed matching algorithms.

Another distributed spectrum sharing algorithm is presented in [36] where each SU selfishly tries to select the best band to transmit which is then modeled as a multi-user restless Markov multi-armed bandit problem, in which multiple SUs collect a priori unknown reward by selecting a channel.

In the underlay CR network model, SUs can utilize the spectrum in parallel with PUs, given the condition that they guarantee not to exceed a predetermined threshold value on the transmission power. Therefore, many works using this network model optimize the QoS related parameters by adjusting the transmission powers and channel selections of SUs, like in [37] and [38] that employ multi-channel, and like [39] that is suited for single-channel environments.

Another work on QoS consideration that is based on many physical layer components and calculations is in [40] where an underlay approach on spectrum access is preferred. The maximum limit on the interference-power that should not be exceeded by the transmission of the SUs and the maximum arrival-rate supported by the SU relaying link to satisfying a statistical delay QoS constraint are presented as well as the closed-form expressions for the effective capacity of the channel in Rayleigh block-fading environment.

Studies in [41] also include an underlay network model and include scheduling and power allocation solutions for an up-link multi-SU CR system. The authors solved the

delay minimization problem in the presence of an average interference constraint to the PU, and an average delay constraint for each SU at cognitive base station (CBS).

A hybrid network model is employed in [42], where the optimal channel selection and the associated power distribution is modeled with mixed integer nonlinear programming problem for which several solution approaches were proposed. Several power levels are defined in this reference work to match with both underlay and overlay CRN models. Throughout the studies in this thesis, an overlay a.k.a interweave network model is adopted and limited to utilize unoccupied PU channels.

In the perspective of PU temporal activity estimation, the expected availability ratio for each channel is defined in [25], where the routing problem is handled including SUs that select single channel for data forwarding. The proposed channel status classification scheme in this thesis (detailed in Section 3.1.2) on channel temporal status behavior, is similar in concept. However, the proposed method is rather a projection on PU activity class that is achieved distributively, whereas the reference works uses the availability vectors of SUs that are retrieved via CCC.

QoS provisioning studies may also exist in Medium Access Control (MAC) layer, like in [43], for single channel access and in [44] for multi-channel (but single-interface) distributed access, to adjust MAC layer parameters accordingly. In [44], channels are sensed in sequential order and if the previous channel is not idle, and QoS discrimination is performed by adjusting the arbitrary channel sensing period length. Several MAC protocols were also devised incorporating both scheduling and spectrum sharing among SUs, like the ones summarized in [45] survey paper.

As noted in [46], in half duplex MAC protocols, where the SUs first need to sense the channel before using it (like the used network models throughout this thesis), SUs need to be synchronized, whereas the proposed scheme in this thesis is an asynchronous one as detailed in Section 3. In [46], the authors proposed a MAC protocol that uses a standard back-off algorithm and derived optimal parameters for full duplex SUs with single transceivers for multi-channel CRN. However, each SU in the described system can utilize only a single channel, whereas in the network model used in this thesis, the SUs can utilize multiple channels in parallel.

In [47], multi-channel multi-interface CRN model is employed. The authors presented an analytical model for deriving several performance metrics based on M/M/k queuing model, in which number of servers referring to the number of available channels that varies over time, and the model is then projected into two dimensional continuous time Markov chain for further analysis. The sensing model employed in this reference work is cooperative sensing, achieved through the CBS, and the SUs are thought to be synchronized unlike the distributed local sensing and asynchronous mode properties of proposed mechanisms in this thesis. Additionally, the SUs deploy a contention based MAC protocol, whereas the distributed scheduling mechanism proposed in this thesis eliminates the need for further contention management. Also in [48], the authors proposed a MAC protocol utilizing the CCC and deciding the owner of a channel by maximum weight scheduling method. Proposed method in [48] is an example of a distributed solution. However, for it to work properly, SUs need to keep a track of the queue sizes of other SUs that they retrieve frequently from the CCC.

Spectrum sensing layer is also adopted and managed, coupled with some QoS constraints in some of the reference works like [49] and [50], in which the authors examined the selection of the number of the spectrum bands to sense concurrently in order to ensure a fixed minimum rate for SUs, while decreasing the sensing delay. In [51], the authors handled the problem of optimizing the sensing and transmitting trade-off in hardware constrained CRNs. Differently, in this thesis, a fast and simple spectrum assignment scheme is proposed that can operate over existing spectrum sensing protocols to provide a performance gain using local spectrum sensing history.

The authors of [52] modeled the cognitive transmission as a state transition model and expressions for the effective capacity of the cognitive radio channel is determined in the presence of QoS constraints. The interactions and trade-offs between the throughput, QoS constraints, and channel sensing parameters are also investigated through numerical analysis.

Although it is neglected in the vast majority of related studies, the channel switching frequency of an SU may also have an impact on the QoS performance as discussed by reference work [34] where the authors proposed a least square difference method to optimize channel switching frequency while meeting QoS demand of SUs. This reference work is an example of a centralized solution and also utilizes geolocation

database (GDB) for channel information like [53] but extended it by considering channel switching cost. Although the proposed spectrum management and scheduling methods in this thesis are still applicable over such systems where a prior PU behavior is known. A more generic architecture using individual spectrum sensing results of the SUs are proposed.

Overall, the thesis studies differentiates from the previous works by the distributed and fast algorithm design on spectrum assignment, aided by the PU temporal activity behavior prediction. Moreover, the spectrum assignment scheme is coupled with a distributed spectrum sharing method that prevents collision among the SUs working in a single collision domain. The proposed methods can be employed in several network paradigms including CRN principles, e.g. 5G technology.

Next Generation Networks and 5G technology is based on the integration of heterogeneous wireless systems and CRNs. In these new network paradigms, many cognitive components will take place to provide more efficient communication environments, like in [54], where the authors coupled CR methodology with machine learning components to achieve better QoS in 5G device-to-device communications. Future 5G networks are likely to introduce dense small cells and Dynamic Spectrum Access (DSA) to enhance system capacity density. In this context, a user is likely to have multiple base stations (BSs) to connect to, and these BSs are allowed to share a common spectrum band utilizing CR technologies as discussed in [55]. CR technology is to be employed in 5G vehicular networks as well, like in [56], where cellular BSs are used by background users and cognitive road side units serve the vehicles. As also noted in [57], 5G mobile networks can also be deployed over the TV white spaces and CR will be employed at spectrum brokers on top of BSs, providing them resources. Heterogeneous QoS provisioning architecture over 5G wireless networks is described in [58], which also includes CR wireless communication for a 5G-candidate technique. CR technology may also be employed in 5G architectures at network operator level to produce spectrum resources to eNodeB components, like described in [59], in which cognitive network operator may listen many heterogeneous primary networks like WiMax and Wi-Fi.

Cognitive capable mobile stations in 5G cellular networks are studied in [60] where the authors managed spectrum hand-off delays by allocating channels based on the

user QoE expectations, minimizing the latency. CBS maintains a ranking index of the available channels to be used in hidden Markov model to predict the state of the future time slot and minimize hand-off delay for users. Then, a priority-based channel allocation scheme is proposed to assign channels to SUs. Another important novelty of the paper is the proposed seamless service method that transmits scalable video coding (SVC) base layer prior to hand-off when a hand-off is predicted. Peak Signal to Noise Ratio (PSNR) is used as performance metric like the performance studies in this thesis along with its Mean Opinion Score (MOS) projection.

Proposed spectrum assignment schemes in this thesis, can also be applied over such cognitive radio enabled components in Next Generation Networks.

2.4 Video Transfer over Cognitive Radio Networks

Traditionally, the traffic characteristics handled by the SUs are expected to have best effort type. However, the continuous emergence of wireless communication devices and the increased user demands necessitate the SUs to handle real time traffic (e.g. video) as well.

Considerable number of related works tackle the QoS provisioning problem for video transfer in a centralized manner, like [61] and [62], which is suited for a single antenna SU. Unlike the network model used in this thesis, these solutions benefit from well defined optimization problems and usage of a centralized entity. In [63], the authors defined a mixed integer nonlinear programming, and also provided sequential fixing algorithm for its distributed implementation. The presented solutions require the estimation of several network parameters and some knowledge like channel information. The authors of [64] couple the spectrum-sensing into the video transfer flow, and reduces number of channels to be sensed. In [65], a video-content-delivery-tailored MAC protocol that divides the channel into more fine-grained sub-slots is presented. Our proposed heuristic scheduling method is way more simpler and extensible, which can work transparently with existing MAC and spectrum-sensing protocols.

In [66], coarse grain scalable (CGS) and medium grain scalable (MGS) extension of the SVC standard are used as the encoding method (that offers temporal, spatial,

and quality scalability) and per-sub-carrier transmit antenna selection, such that spatial diversity is exploited, is proposed with a binary integer program which optimizes terms of the aggregate visual quality of received video sequences of all SUs. While CGS supports only a predefined set of rate-distortion points, a more flexible rate adaptation is possible with MGS. The staircase rate-distortion characteristics of CGS/MGS sequences is exploited by the proposed method not to allocate more than necessary resources to attain a given visual quality. An underlay network model assisted by a Cognitive Base Station (CBS) was used. CBS knows the channel gains between SU transmitter/receiver and SU transmitter/PU receiver couples, an integer programming formulation could be defined, that maximizes the aggregate PSNR of the received video sequences at the cognitive receivers under the received interference power limit imposed by the primary system and the rate assigned to each user. The binary integer program can be solved using discrete programming methods such as the branch-and-bound technique but it is not very suitable for fast changing environments. The video transfer model in [66] differs from the one used in this thesis as the CBS sends MGS/CGS video sequences as down-link to CR users using Orthogonal Frequency Division Multiple Access (OFDMA). CGS downlink video streaming to multiple SUs is studied in [67] as well, where the CBS adaptively assigns the available channels to the SUs while taking into considerations their buffer occupancies. In the network models employed in this thesis, a more flexible an ad-hoc video transmission model is adopted such that distributed SUs may send traffic requests to any receiver SU within its transmission range.

In, [68] SVC and transmission rate adaptation (TRA) are jointly considered in an energy-efficient scheme for the transmission of streaming media over a CRN. Related work is intended to be a cross-layer method as SVC is employed at the traffic layer and TRA, that uses adaptive modulation and coding (AMC) and/or transmit power control, at the link layer. The QoS requirement of video traffic is considered as the main constraint, and the minimization of transmission energy consumption is pursued as the objective of optimization. An event-driven discrete-time Markov control process model is introduced to formulate the QoS-guaranteed energy-efficient transmission problem as a constrained stochastic optimization problem. An online potential

estimation and stochastic approximation is also proposed that does not depend on any a priori channel information [68].

In [69], the proposed probabilistic approach tries to mitigate total interference caused by SU transmitter to PU receiver considering imperfect channel state information. The authors presented a new closed-form expression for deterministic approximation of the probabilistic PU transmitter interference constraint for solving formulated optimization problem. The authors also defined and used several tolerable collision levels of PUs that are changing with PU traffic types. A deadline approach is also employed that reflects the time by which the frame must be received at the downlink receiver to ensure uninterrupted play-out In this thesis, a similar timeout mechanism is used for the packets including delay-sensitive video frames.

In [39], optimal spectrum sensing and access problems are studied separately and matching-based optimal algorithms were proposed to the sub-problems. The authors again benefited from the centralized network structure where a downlink multi-user video streaming in cellular CRNs is studied. The network environment used in [39] includes a single CBS and multiple SUs that cooperatively sense PU signals.

Like spectrum sharing studies, game theory is also utilized for multimedia transmission over CRNs which considers the game players' selfish behavior. In [70], the authors stated that as SUs may need huge amount of data storage and processing power for several cognitive functionalities, a cloud network would become handy. They proposed a user-oriented CR cloud network for multimedia applications, where the user's satisfaction is reflected in the CR cloud network design where the PU and the SU games are formulated as Stackelberg games and the related NE were proved. The SUs perform some payment to PUs as the PUs are defined as game leaders. A refunding mechanism, according to which the SUs can get part of their payment back based on the retrieved QoE satisfaction level, is also incorporated into the game definition. The proposed method outperforms a similar game theory method which did not consider the user's QoE requirements. The authors used PSNR of the received multimedia information as an objective QoE metric, in parallel with the performance metrics used in this thesis.

As listed by the survey paper [71], the challenges of the video transfer of CRNs are:

- *Spectrum sensing:* A reliable spectrum sensing is highly coupled with the video transfer quality. There is a trade-off between the spectrum sensing reliability and the packet transmission delay. Trying to identify more idle channels, SUs usually require a longer spectrum sensing time, which shortens the video transmission time and causes a larger transmission delay.

- *Modulation and coding schemes:* QoE is also dependent on other factors such as bit error rate and delay, which are affected by the chosen video modulation and coding scheme and the channel conditions. Therefore, the design factors have to be jointly optimize multiple design factors, such as spectrum sensing, modulation and coding scheme selection for QoE provisioning.

- *QoE model:* MOS is the average score of a tested video, and degradation MOS (DMOS) metric is obtained by averaging the arithmetic difference between the scores of the source video and the processed video. Both MOS and DMOS are subjective metrics.

  Defining an objective quality metric is a challenge. *Moving picture quality metric*, *perceptual video quality measure*, and *visual signal-to-noise ratio* are often modeled as a function of network parameters (e.g., packet loss rate, transmission delay, and jitter), coding parameters (e.g., bit rate and frame rate), and some external factors such as video content type, viewer demography, and device type.

  Pure objective metrics can be listed as the PSNR and Mean Structural SIMilarity (MSSIM).

- *CR related challenges:* CR inherited challenges include the QoE-driven spectrum hand-off scheme and power adaptation for constraining the PU interference.

- *Admission control:* An admission control needs to be performed for limiting the number of active video sessions such that each of them can have a satisfactory QoE.

- *Channel allocation and routing:* The available channels found by SUs may be significantly different in frequency, channel gain, and available time for transmission which makes channel allocation and routing crucial.

- *Frequency reuse:* Frequency reuse among different sessions may be implemented to further increase QoE support in multi-user video streaming.

- *Adaptive modulation and coding:* When the channel conditions are good, adaptive modulation coding schemes with larger constellation sizes and higher channel coding rates are preferred. The goal is to minimize the expected video distortion while keeping the packet loss at an acceptable level, considering that channel availability may quickly change over time. These coding variants come with the increased decoding complexity.

  As the channels are not always available over time, SUs should encode the video sequences using a strong coding scheme. It may then take a longer period of time for the receiver to receive and decode the video sequence. The quantization step size in encoding also can be optimized to achieve a trade-off between distortion and delay.

- *Buffer storage management:* Resource buffer (RB) of video transmission may be depleted (i.e., buffer underflow) if the channel is bad or unavailable for an extended period of time. Some reference works propose lowering the play-out speed of the video sequence to a certain extent to decrease the probability of play-out outage, when the RB becomes hungry. This is based on the observation that varying the video play-out rate by 25 to 50 percent could be unnoticeable and therefore acceptable. Another solution is to solve this problem by allocating channels according to the buffer storage of the SUs. SUs may have different channel data rates and different buffer storage sizes, which result with different abilities to tolerate network dynamics.

SU energy consumption, as encoding and decoding a video require a lot of computation and consume considerable power, *SU feedback* mechanism, especially when there is no CCC, *admission control for SVC videos*, *QoE modeling*, *security and privacy* and *emerging new applications*, like a 3D video transmission, can be listed as open problems and future directions.

A distributed queue management scheme is proposed in this thesis that uses the frame type information inside the video packets to be transmitted, and provides a more intelligent protection for a probable packet loss that results from the dynamic nature

of the SU spectrum availability. The objective video quality metrics used in this thesis are listed as: PSNR, Mean Structural SIMilarity (MSSIM [72]), and Q, which is the decodable frame ratio over the total number of frames.

3. NEW CHANNEL SELECTION AND SCHEDULING METHODS IN COGNITIVE RADIO NETWORKS

In this chapter, a channel assignment algorithm that couples an estimation of the PU activity temporal level with the SU packet selection is proposed. Temporal PU activity level is estimated by the distributed SUs that only use their local sensing histories via projecting the moving average value of their individual sensing histories into three temporal activity classes. This classification is then incorporated into packet selection from different QoS level queues.

The motivational intuition which is exploited in designed methods is that a highly occupied channel, in terms of the temporal PU activity, may not serve well a high prioritized (HP) and delay sensitive SU traffic such as real time video traffic. If such a channel is used, SU packets would be interrupted by incoming PUs more often and the probability of these packets to be timed-out increases due to their increased waiting times. Using these kind of spectrum opportunities would result with better overall network utility when low prioritized (LP) packets, that are not delay-sensitive, were selected to be transmitted instead. In contrast, native methods in CR networks commonly try to select the most prioritized SU packets whenever an opportunity arises. These schemes tend to send a packet without considering the channels' future temporal behavior as long as the channel capacity is sufficient for a packet transmission. However, when serving heterogeneous traffic classes, strategies like selecting the best channel or giving all the available resources to the most QoS demanding queue may not always provide better results in terms of the overall resource utilization and user experience, as will be demonstrated in the following sections. Therefore, a channel status prediction is incorporated to characterize the PU channel temporal activity and provide valuable assistive information for channel selection.

The devised heuristic cognitive channel selection algorithm was first introduced in [73]. This reference work introduced the main approach used in the SU packet selection algorithm and presents some preliminary results for a single SU and a single

channel environment. Section 3.1 includes the network model, the design principles and the performance results for this environment.

In the related previous work [74], the distributed packet selection algorithm proposed in [73], which uses the outcome of PU temporal behavior prediction on a single channel, is expanded into a multi-channel spectrum assignment scheme, utilizing similar heuristics using local and temporal PU activity level prediction. The network model is expanded also to include multiple SUs. To alleviate the problem of managing conflicting interests of distributed and selfish SUs within a single collision domain, a distributed scheduling mechanism is also proposed. Coupled with the spectrum assignment scheme, the proposed mechanisms were designed to be well suited for multi-channel and multi-user environments, where the SUs have multi-interface capabilities. Both spectrum assignment and scheduling algorithms were evaluated and compared with the native spectrum assignment scheme and random scheduling in several environments. Section 3.2 includes the network model, the design principles and the performance results for this environment.

All proposed methods are implemented in MATLAB® and several simulations were performed. The simulation results show that the proposed method is advantageous in terms of the *Figure of Merit (FoM)* metric defined by the weighted sum of throughput ratios of the packets successfully reached at to destination. The proposed method, which basically is a fast PU temporal activity level prediction and a channel selection scheme, reflects its advantageous side especially when the spectrum holes belong to a heavily used PU channel. The performances of these two network models and the proposed schemes can be seen in Section 3.1.4 and Section 3.2.4, for single-user-single-channel and multi-user-multi-channel environments, respectively.

3.1 Channel Selection for Single-Channel, Single-User Cognitive Radio Environment

Aiming to increase the overall network utility for an SU with traffic requests at different QoS levels, a packet selection algorithm is designed that uses channel's temporal status prediction. In this section, in order to reflect the motivational heuristics in the simplest network scenario, a single SU that utilizes a single PU channel in a cognitive manner is employed.

The network model is presented in detail in Section 3.1.1. The details of PU channel prediction scheme and the packet selection algorithm are given in Section 3.1.2 and Section 3.1.3, respectively. Section 3.1.4 includes the performance evaluation of the proposed packet selection scheme.

3.1.1 Network model

In the employed network model, PUs have Poisson traffic patterns with means of μ_{ON} and μ_{OFF} for their on and off periods, respectively. The PU traffic signal is modeled having predetermined amplitude levels for these periods. Any SU is allowed to use a channel when the corresponding PU on that channel is in an off period, effectively employing the *overlay* approach.

SUs are designed to work in a time slotted manner, managed by the sampling period denoted by t_s. SUs sample the continuous PU activity at the beginning of each t_s. Even if the sensed PU signal may have any amplitude, SUs employ a threshold mechanism like an energy-detector-based spectrum sensing and provide a binary spectrum sensing status. This binary decision is valid, and it is used for the next t_s period of time. As the spectrum sensing methodology is beyond the actual scope of this work, further physical layer constraints are not modeled (e.g. the received SNR of the PU transmitter at the SU receiver).

Figure 3.1 depicts the interactions between a single PU and a sensing SU. The arrows in this figure visualize the instantaneous spectrum sensing instances. Upon the discovery of a vacant channel, the SU takes a packet from one of its traffic queues and performs its transmission. SU packet processing and transmission times are assumed to be representable by a constant parameter. In Figure 3.1, for simplicity and without the loss of generality, while representing the service time behavior of an SU, the total packet processing and transmission delays are modeled with $1 * t_s$ (i.e., a single packet is transmitted within a single slot). A packet residing in an SU traffic queue will then be served with rate $1/t_s$ as long as the PU is inactive. The service time will increase directly proportional to PU active period as seen in Figure 3.1. Specifically, the probability distribution of the SU service time in the described system can be approximated using the exponential distribution properties of the PU on and off periods, as given in (3.1) (see Appendix 6 for the details of this approximation).

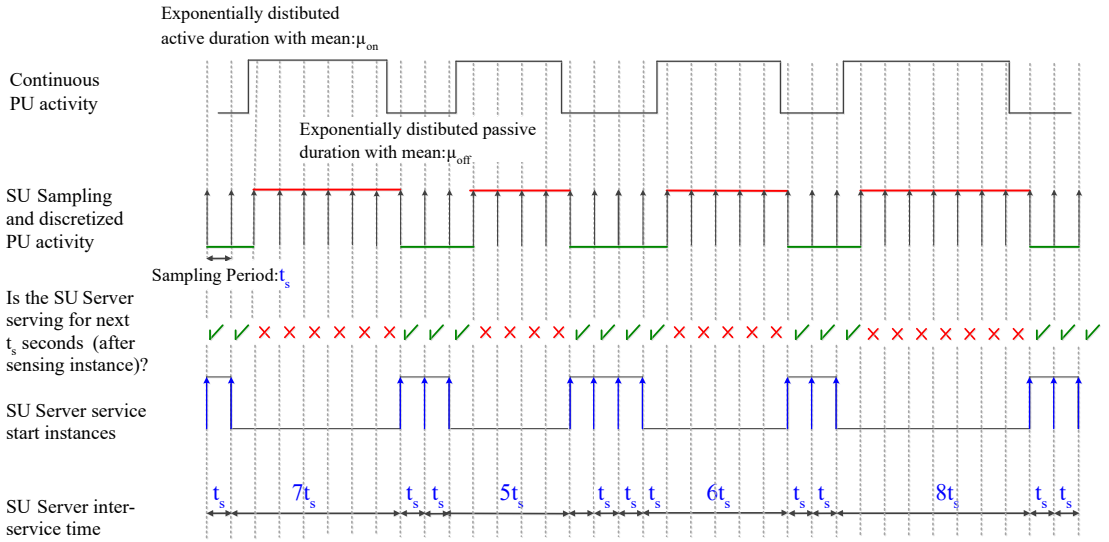


Figure 3.1 : SU-PU interactions and SU service behavior.

$$\Pr\{serviceTime = n * ts\} = \begin{cases} 0 & n < 1 \\ \frac{\frac{\mu_{off}}{t_s}}{\frac{\mu_{off}}{t_s}+1} & n = 1 \\ \frac{1}{\frac{\mu_{on}}{t_s}+1} e^{-\lambda t_s (n-2)} (1 - e^{-\lambda t_s}) & n > 0 \end{cases} \tag{3.1}$$

$$given : \lambda \stackrel{\Delta}{=} \frac{1}{\mu_{on}}$$

It has to be noted that by the presented instantaneous spectrum sampling model, the time consumption of the sensing phase becomes negligible. However, a proportional spectrum sensing period with respect to the packet processing and the transmission time can be incorporated without any effect on the performed analysis by adjusting the server service time.

The traffic requests of SUs are discriminated in two QoS classes, and related packets are kept in two separate queues, named *HP packets queue* and *LP packets queue*. HP packets are designed to have associated time-out mechanism reflecting their reneging behavior: an HP packet is dropped when its waiting time exceeds a predefined threshold value denoted by τ_{delay}. In the described system, HP queue is a model of an $M/G/1$ queue with deterministic reneging times for which the analysis is given in [75]. As it also can be seen from [76], the probability of packet loss rate due to the reneging behavior increases with increased traffic intensity. Therefore, a channel selection algorithm is devised, aligned with the main phenomenon that the probability

of packet loss increases with the decreased service rate, which uses this information on the channel selection in favor of increasing the overall network utility.

The parameters used in the network model along with their notations can be seen from Table 3.1.

Table 3.1 : Model parameters and notations for both single and multi-channel environments.

Notation	Explanation
μ_{ON}	PU ON period mean (exponential dist.)
μ_{OFF}	PU OFF period mean (exponential dist.)
$D = \frac{\mu_{ON}}{\mu_{ON}+\mu_{OFF}}$	PU duty cycle
τ_{delay}	Tolerable delay per node (for high priority traffic packets)
$\|Q_{HP}\|$	High priority traffic queue size for each SU
$\|Q_{LP}\|$	Low priority traffic queue size for each SU
$\|W_H\|$	PU Activity moving average circular window size in time units
T_H	High priority CBR traffic inter-arrival time
T_L	Low priority CBR traffic inter-arrival time
T_{SIM}	Simulation time
t_s	Sampling time
k	FoM weighting factor of high priority packets

3.1.2 The proposed channel status classification method

In this work, the channel status prediction is incorporated to characterize the PU channel that is sensed as unoccupied, and this prediction is used by any SU for its transmission. This characterization aids the SU packet selection assignment scheme aiming to provide performance gain by selecting the channel to be used in a more intelligent way. The PU status prediction method is basically a classification of a channel in terms of its temporal PU activity using the previous sensing history of a specific window size.

Each sensing instance of an SU results in a binary spectrum sensing status, representing whether a PU traffic is present or not on the sensed channel. Each SU records its local binary sensing history in a circular window of size $|W_H|$ that always keeps the last $|W_H|$ sensing decisions after an initial-fill period.

The channel classification operation is performed whenever an SU detects a spectrum hole. The instantaneous average of the spectrum sensing results in the circular window

at hand is projected to a PU class to map to one of three classes: *heavy use*, *moderate use* and *sparse use*. Since the average of these recorded binary spectrum sensing decision samples will result in $[0,1]$ interval, classifier thresholds are defined as: 0.33 and 0.66, dividing this interval into three uniform regions of $[0,0.33]$, $[0.34,0.66]$ and $[0.67,1]$, representing channel labels of *sparse use*, *moderate use* and *heavy use*, respectively. A uniform averaging approach is preferred as each of the PU samples in the spectrum sensing history window has equal importance in terms of estimating the temporal status of the PU. Moreover, a simple projection and estimation scheme is implemented as this rough number of levels (*heavy use*, *moderate use* and *sparse use*) were sufficient to reflect the advantageous side of the algorithm, coupled with the motivational observations. After this classification result is obtained along with a spectrum hole detection for the observed channel, the packet selection method selects the next packet from the appropriate queue.

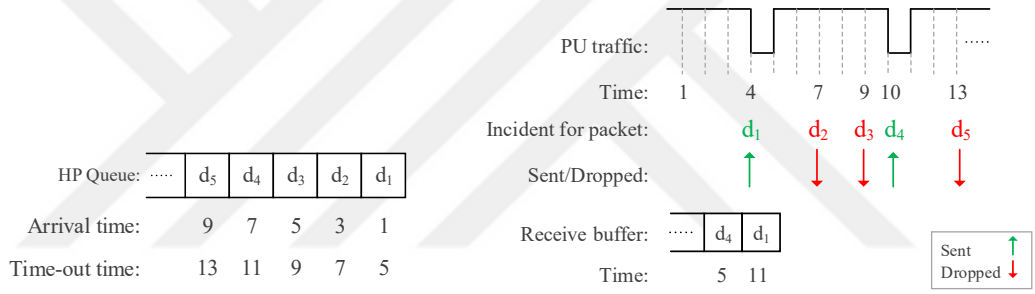
3.1.3 The proposed packet selection method

In this work, the packet/channel selection algorithm is designed with a heuristic method based on the motivational observations. LP packets, that do not have any delay constraints, are leveraged over HP packets for channels with more frequent PU activity. Similarly, for sparsely used channels, HP packets are selected over LP packets.

A channel having a PU activity as *heavy use* may be vacant for a small period of time, but it will be occupied within a very short time afterwards. With the native strategies, whenever this channel -indeed any channel who has sufficient capacity to transmit a single packet- becomes idle, a high demanding traffic packet will be served. Resulting from the fact that the interval between the spectrum hole opportunities in a heavily used channel is high, the received HP packets will have high inter-arrival time, along with some missing packets in between. Both of these effects may cause such a considerable disturbance in terms of Quality of Experience (QoE) that these minor number of non-sequential received packets may also be treated as lost with regard to the QoE. This phenomenon is directly related to the nature of HP packets. What is referred with HP traffic is a delay-sensitive and data-sequence-sensitive traffic type (like streaming video traffic) for which the delay between consecutive packets and the

number of packets lost in between has a large impact on the perception quality of the user.

A demonstration is presented in Figure 3.2, where the inter-arrival times of the HP packets and their time-out thresholds are 2 and 4 time units, respectively. The queue entering times and time-out deadlines are depicted as in Figure 3.2(a). For the sake of simplicity, a single time unit is supposed to be enough to serve a single HP packet, and the receiver is supposed to be in the next hop. In Figure 3.2(b), data send and time-out drop incidents along with the received packets can be seen. The receiver will receive 1^{st} and 4^{th} data packets with a 6 units of inter-arrival time between them. This and potentially increased high inter-arrival time at the receiver side may result in a negligible contribution by these packets in terms of QoE for some delay sensitive traffic types.



(a) Data arrival times and timeout schedules.

(b) Data send/drop incidents and receive buffer.

Figure 3.2 : Sample transfer of HP packets over a heavily used channel ($T_H = 2$, $\tau_{delay} = 4$, $\mu_{ON} = 5$, $\mu_{OFF} = 1$).

In addition to their increased inter-arrival times, the received HP packets may also not result in a valid contribution to QoE because of the data packets lost in between. A common example is when the disturbance observed by a user watching a streamed video caused by dropped frames in between, is so much that the perceived video does not make sense. The main motivation of the proposed selection schemes is to predict such possible pseudo loss of HP packets over heavily used PU channels, and use their spectrum opportunities for LP packets instead.

After a classification result is obtained along with the spectrum hole detection, the proposed packet selection method, seen in Algorithm 1, runs to select one of the packets in one of the queues.

Algorithm 1
SU packet selection algorithm in single channel environment

Require: Binary spectrum sensing result: x^t,
Integer PU classification result: c^t (1: *sparse use*, 2: *moderate use*, 1: *heavy use*),
Current SU Queue Sizes: ${q_{hp}}^t$, ${q_{lp}}^t$.
$send_{hp} \leftarrow 0$ ▶ Binary decision vector for sending HP packet
$send_{lp} \leftarrow 0$ ▶ Binary decision vector for sending LP packet
if $x^t = 0$ **then**
  if $c^t = 1$ **then** ▶ Channel classified as in *sparse use*
    if ${q_{hp}}^t > 0$ **then** ▶ Favor HP traffic
      $send_{hp} \leftarrow 1$
    else if ${q_{lp}}^t > 0$ **then**
      $send_{lp} \leftarrow 1$
    end if
  end if
  if $c^t = 2$ **then** ▶ Channel classified as in *moderate use*
    if ${q_{hp}}^t > 0$ **and** ${q_{hp}}^t > {q_{lp}}^t$ **then** ▶ Select greater queue size
      $send_{hp} \leftarrow 1$
    else if ${q_{lp}}^t > 0$ **then**
      $send_{lp} \leftarrow 1$
    end if
    if ${q_{lp}}^t > 0$ **and** ${q_{lp}}^t > {q_{hp}}^t$ **then**
      $send_{lp} \leftarrow 1$
    else if ${q_{hp}}^t > 0$ **then**
      $send_{hp} \leftarrow 1$
    end if
  end if
  if $c^t = 3$ **then** ▶ Channel classified as in *heavy use*
    if ${q_{lp}}^t > 0$ **then** ▶ Favor LP traffic
      $send_{lp} \leftarrow 1$
    else if ${q_{hp}}^t > 0$ **then**
      $send_{hp} \leftarrow 1$
    end if
  end if
end if

The packet selection strategy is developed to reflect the motivational principles. If the channel is classified as in *heavy use*, LP packets are selected. Similarly, when the channel is classified as in *sparse use*, HP packets are selected. If any of the queues, that the initial priority is given, is empty, a packet from the other queue is selected not to lose a spectrum hole opportunity. For the *moderate use* case, the selection is performed using current queue sizes of both queues and a packet from the queue having larger queue size is selected. The *moderate use* case of PU channel classification actually does not provide a very discriminated information in terms of performance gain by preventing packet losses on HP traffic flows. Therefore, a more balanced assignment scheme is preferred, and both types are supported taking their related queue sizes into account.

3.1.4 Evaluation of the proposed methods

In this section, the proposed channel status prediction and packet selection mechanisms are evaluated for various environments. All methods are implemented on top of a detailed MATLAB Simulink® model for which several model views are included in Appendix 6. Components of SimEvents® are used for the queuing mechanisms. Environment model development phase includes sub-components like modeling the PU traffic, modeling SU traffic requests with two types of QoS levels, the modeling and the arrangement of the SU packet queues, and all related management signals such as dequeue signals.

The proposed packet selection algorithm, the spectrum sensing history and the classification modules are also implemented within the designed MATLAB Simulink® model that is supported with a lot of informative elements for performance measurements.

In the simulations, the inactive period mean of the PUs (denoted by μ_{OFF}) is fixed to a certain value and the active duration mean (denoted by μ_{ON}) is swept, resulting with several duty cycles. Therefore, in the simulation results, increasing the duty cycle directly refers to an increase in the PU activity.

An important performance metric, namely *Figure of Merit (FoM)*, is defined to cover the quantitative performance gain in terms of throughput and incorporating QoS discriminated gain. FoM formulation is given in Equation 3.2. *Throughput Ratio* is defined as the ratio of the number of packets successfully reached to the destination denoted by $HP_{success}$ and $LP_{success}$ for HP and LP packets respectively, over the number of packets generated by the source SU throughout the simulation time denoted by HP_{total} and LP_{total} for HP and LP packets correspondingly. The *FoM* is then defined as the weighted sum of the throughput ratios of the HP and the LP packets. A unit weight is provided to the LP packets, whereas the weight of the HP packets is denoted by k, is varied in the parametric simulations. The parameter k emulates the discrimination of the HP and the LP packets in terms of their relative worth, and the value of this parameter can be adjusted further in the field to reflect other factors, such as pricing.

$$FoM = \frac{k * HP_{success}}{HP_{total}} + \frac{1 * LP_{success}}{LP_{total}} \tag{3.2}$$

The presented results are averaged over 15 runs, and the 95% confidence intervals are indicated. In addition to the proposed method, a native channel assignment scheme which is referred to as *"Native Scheme"* in the performance result plots is also implemented. The native scheme basically selects HP packets upon any spectrum opportunity and gives chance to LP packets only if the HP queue is empty at a particular time instance.

The network model used in a single channel, single contending user environment consists of a single SU source node, one SU relay node, and one SU destination node. Source and relay SUs have separate queues for the HP and the LP packets. Incoming SU traffic types at SU source node were modeled using constant bit rate (CBR) for both traffic types along with different rates for HP and LP types. The source and the relay SU nodes act as transmitters, sending the packets to the relay and the destination SUs, respectively. SU source and relay nodes monitor different PU channels which have the same duty cycle.

3.1.4.1 Throughput performance

Parameter settings used in these set of simulations can be seen in Table 3.2. The time dependent parameters like μ_{ON}, μ_{OFF}, τ_{delay}, T_H, T_L, T_{SIM} and t_s are given in unit of a single step of discrete event simulator of MATLAB Simulink®. In the simulation results, increasing duty cycle directly refers to an increase in the PU activity.

Table 3.2 : Parameters for the single channel environment simulations.

Notation	Value/s
μ_{ON}	Calculated for each D
μ_{OFF}	4
$D = \frac{\mu_{ON}}{\mu_{ON}+\mu_{OFF}}$	$\{0.1, 0.2, 0.3, 0.4, 0.5$ $0.6, 0.7, 0.8, 0.9\}$
τ_{delay}	10
$\lvert Q_{HP} \rvert$	inf
$\lvert Q_{LP} \rvert$	inf
$\lvert W_H \rvert$	100
T_H	1
T_L	2
T_{SIM}	1000
t_s	1
k	$\{1.0, 1.1, 1.2, 1.3, 1.4, 1.5,$ $1.6, 1.7, 1.8, 1.9, 2.0\}$

Figure 3.3 depicts the FoM values with respect to varying PU duty cycles for different k values. FoM metric, by definition, represents the combined performance of HP and LP packets. As it can be seen from this figure, the proposed scheme performs the same as the native scheme for low duty cycles and outperforms the native scheme for all the duty cycles after 0.2. For the first two duty cycles, the PU traffic can be referred as sparse. When the PU traffic is classified as in *sparse use*, the behavior of the proposed algorithm becomes identical to the native scheme: mostly selecting HP packets, and selecting LP packets only if the HP queue is empty. Therefore, in those duty cycles, both schemes behave the same, resulting with identical FoM performance. It can also be seen that, in general, the proposed scheme increases the FoM. This behavior demonstrates the beneficial side of the proposed packet selection algorithm. Even if the weight of the LP packets at the FoM calculation is lower, as the number of packets delivered to the destination increases, the overall FoM also increases. It has to be noted that this gain in FoM is also reflecting a direct increase in the network wide spectrum hole usage efficiency.

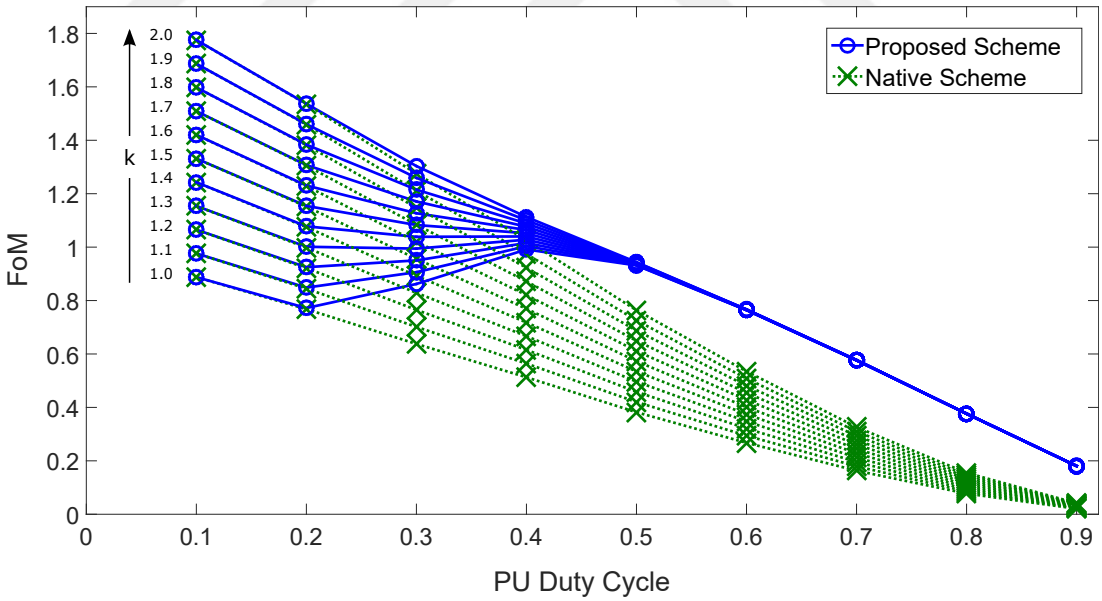


Figure 3.3 : Figure of Merit (single channel assignment).

The effect of the k parameter can be seen in Figure 3.3 where the FoM values are depicted with horizontally discriminated lines with increasing k values. From this figure, it can observed that increasing k value increases the FoM of the native scheme, even if this gain gap decreases with increasing PU duty cycle. As the native scheme

tries to deliver HP packets in higher ratio than the proposed scheme, the effect of k is more directly reflected on the FoM value. However, for the proposed scheme, as the duty cycle of PU increases, the effect of k value decreases. The reason for this phenomenon is that the proposed scheme is biased to take LP packets when the PU activity is classified as in *moderate use* or *heavy use*, thus decreasing the throughput ratio of the HP packets and decreasing the effect of k in FoM calculation in turn.

The packet loss ratio is visualized in Figure 3.4. The depicted packet loss rate values are related to HP packets, as LP packets do not suffer from such additional packet dropping mechanism. In Figure 3.4, an increasing rate is seen for both channel selection schemes for increasing PU duty cycles. Considering the decrease in the number of spectrum holes with increased PU activity, this general trend is expected. In turn, decreased spectrum availability increases the delay on both types of packets, that may result in a packet loss for HP packets.

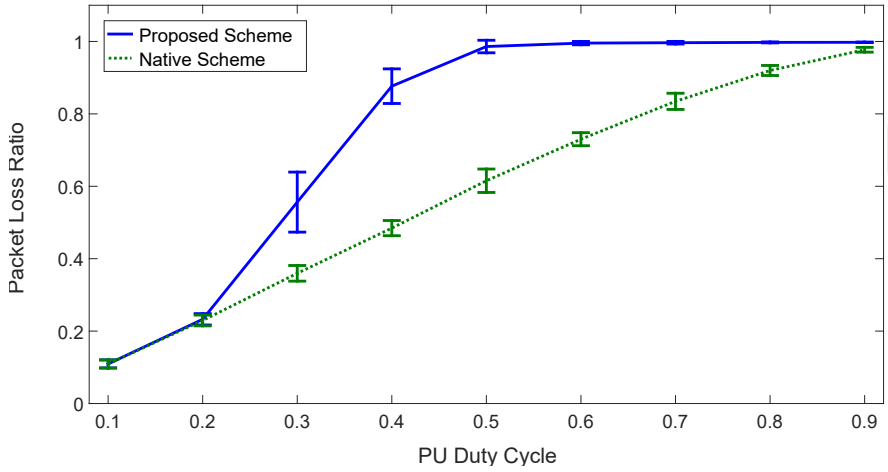


Figure 3.4 : HP only packet loss rate.

Proposed scheme has higher packet loss ratio in the duty cycles where the PU channel is classified as in *moderate* or in *heavy* use. Observed increased packet loss rate comes from the balanced packet selection property of the proposed scheme among HP and LP packets in the *moderate* region, and dominant selection of LP packets in the *heavy* region, whereas the native scheme selects only HP packets in all regions. As proposed heuristics intentionally omit sending HP packets during some opportunities (i.e. spectrum holes of heavily used channels), the HP packet loss rate of the proposed scheme is higher than the native scheme, as expected. Here, it also has to be noted

that the packet loss ratio is calculated by the ratio of the number of lost packets over transmitted packets.

The packet loss performance solely may not be a proper metric when the nature of the HP traffic type is considered. The results seen in Figure 3.4 has to be coupled with Figure 3.3 results, where it can be seen that the overall performance is increased in terms of FoM despite of increased packet loss in some regions. The received HP packets with a very large inter-arrival time and some lost data in between, may not provide any QoE achievement at all. Increased FoM is an indicator of an increased overall network utility in terms of spectrum hole usage efficiency even without reflecting the negative effects of receiving non-sequential HP packets and increased inter-arrival times.

The performance of the uniform weighted moving average estimation on PU classification is also monitored by measuring *PU Classification Accuracy*. Figure 3.5 visualizes the classification accuracy for varying PU duty cycles.

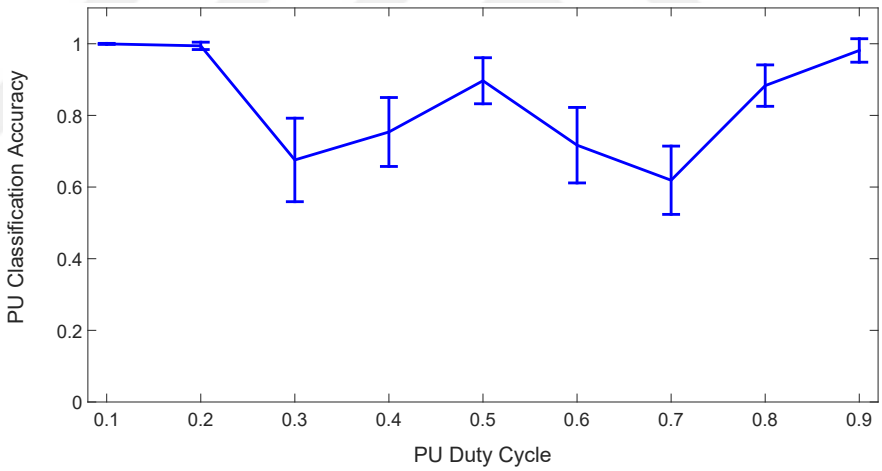


Figure 3.5 : PU classification accuracy with respect to varying PU duty cycle.

As it can be seen from Figure 3.5, the uniformly weighted moving averaging estimation has a very high accuracy with given window size. The performance of the estimator degrades at the duty cycles near to the state transition thresholds (i.e. 0.33 and 0.66). Therefore, for the sparse and heavy channels, a very high classification accuracy is achieved whereas the moderate channel classification suffers from the noise in both directions. This behavior is also expected as a simple and fast estimator is used. The reason for this design choice is that the most important classification of the states of interest were the sparse and the heavy classes rather than the moderate class, in which

the algorithm balances the HP and the LP traffics, while trying to achieve a balanced FoM.

3.1.4.2 Adaptivity property

The adaptivity of the proposed scheme is investigated with respect to PU activity changes during SU lifetime. PU activity pattern in terms of temporal classes may not drastically change within a short period of time, however, the proposed mechanisms should still be able to adopt to the changes in PU traffic to differentiate themselves from static channel selection mechanisms.

The network topology used in this set of simulations is identical to the one used in the simulations given in Section 3.1.4.1, containing a single SU sender, a single SU relay and a single SU destination. The simulation parameters were also identical to the parameters given in Table 3.2, except for the updated ones that are listed in Table 3.3. PU duty cycle parameter is varied between given parameters in Table 3.3 throughout the simulation (at each %10 of the simulation time).

Table 3.3 : Updated parameters for the single channel environment, adaptivity focused simulations.

Notation	**Value/s**
$D = \frac{\mu_{ON}}{\mu_{ON}+\mu_{OFF}}$	$\{0.1, 0.8, 0.3, 0.5$ $0.7, 0.1, 0.9\}$
T_{SIM}	5000

FoM metric is snapshotted at each D update instances throughout performed simulations. 20 runs were averaged and results given within 95% confidence intervals.

Adaptivity property of the proposed channel selection scheme can be seen in Figure 3.6. The proposed scheme outperforms native scheme aligned with the observations of the single-channel environment simulations. As for the sparsely used channels, since both schemes perform identical, their FoM is identical as well. As it can be seen from Figure 3.6, the SU adopts to the varying PU duty cycles throughout the simulation time: FoM increases as the PU duty cycle decreases and acts oppositely as the PU duty cycle increases. This adaptivity property comes from the design of the moving average window based PU channel classification that is adaptive intrinsically.

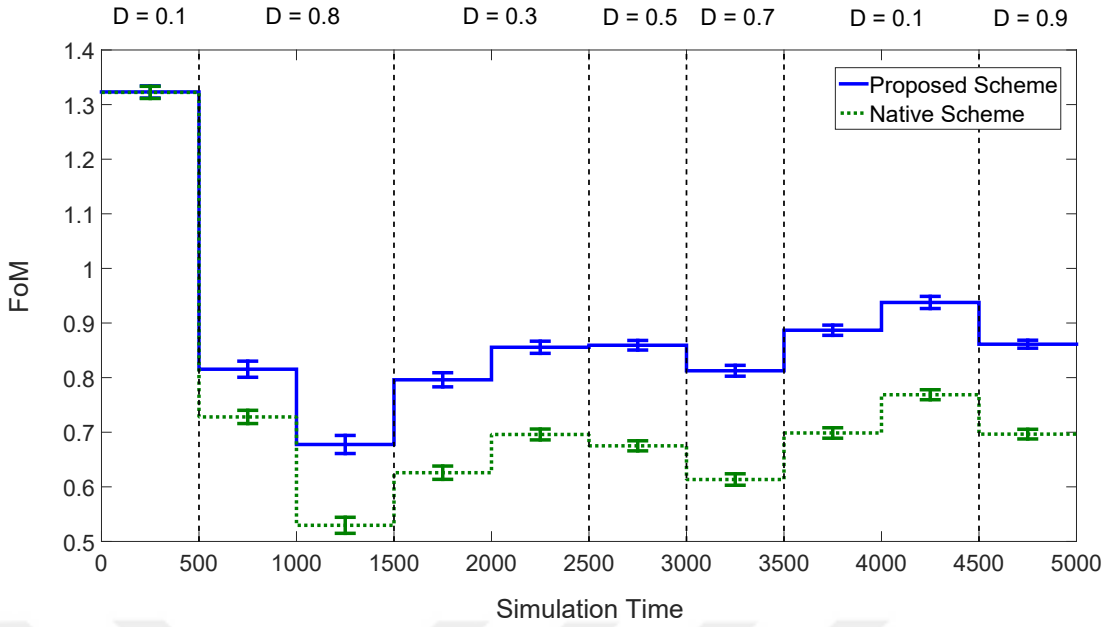


Figure 3.6 : Adaptivity of the proposed channel selection scheme in single channel environment.

3.2 Channel Selection and Scheduling for Multi-Channel, Multi-User Cognitive Radio Environment

The main objective of the proposed work in this section is to increase the overall network utility for the SUs with traffic requests at different QoS levels in a multi-channel and multi-user overlay CRN environments, where the SUs are allowed to utilize the spectrum holes only upon PU absence. The same motivational fact described in Section 3.1.3 is utilized: a highly occupied channel, in terms of temporal PU activity, may not serve well a high prioritized and delay sensitive SU traffic, as SU packets would be interrupted by incoming PUs more often, thus the probability of these packets to be timed-out increases due to their increased waiting times.

Channel status prediction described in Section 3.1.2 is incorporated in this work as well to characterize each of PU channel temporal activity and provide a valuable assistive information for channel selection.

The cognitive channel selection that was introduced in [73] and the details of which are given in Section 3.1 is expanded into multi-channel spectrum assignment scheme using similar principles and supported by various simulations. Moreover, a distributed

SU scheduling mechanism is proposed to assist spectrum assignment algorithms to support multi-channel and multi-user environments.

The details of the used network model and the packet selection algorithms are given in Sections 3.2.1 and 3.2.2. Next, an accompanying scheduling solution among multiple contending SUs is proposed as detailed in Section 3.2.3 for further improvement in overall network utility. Section 3.2.4 includes performance evaluation of the proposed mechanisms.

3.2.1 Network model

In the employed multi-channel, multi-user cognitive radio network model, each channel is associated with an independent PU traffic that is modeled with the Poisson distribution similar to the single-channel model described in Section 3.1.1. SUs employ parallel sensing on each PU channel and retrieve sensing results of all channels in parallel at an instance.

The SU transmitter can send packets simultaneously from all available channels by utilizing channel bonding and channel aggregation techniques. IEEE 802.11n and IEEE 802.11ac standards have adopted the concept of channel bonding referring to the bundling of multiple adjacent channels [77]. Channel aggregation on the other hand refers to bundling of non-adjacent channels and employed in network technologies like LTE-Advanced, in which 4G mobile operators are allowed to aggregate spectrum from non-adjacent bands to support links with high demands [24]. Any channel aggregation or bonding technique comes with several additional costs like hardware costs of multiple number of antennas and software costs of management of several channels in parallel. Due to these practical issues, a limit on the number of channels to be aggregated by SU transmitters can be incorporated transparently to the proposed schemes. The multi-channel usage capability of each SU is also known as *multi-interface* property of SUs, reflecting multiple hardware for using multiple channels in parallel. As also noted in [47], technological advances in antenna design made it possible to fabricate multiple antennas on a single device, such that each interface can adaptively change its operation frequency and radiate in a broad range of spectrum, with uniform performance gain and reasonable size.

The network system architecture can be seen in Figure 3.7. SUs sense the channels individually, and each utilize unused channel/s independently in an ad-hoc manner. There also exists a limited common control channel (CCC) connectivity to the Secondary Base Station (SBS). As a CCC has to be maintained by the unused channels and can easily get overloaded by the use of all SUs, the communication using a CCC is kept limited. In the employed model, each SU takes spectrum usage decisions independently as it will be detailed further shortly. Limited CCC usage takes place only at the initial setup, and upon any topology change to assist spectrum scheduling method as presented in Section 3.2.3, but not for more frequent assistance neither in spectrum decision nor each scheduling period.

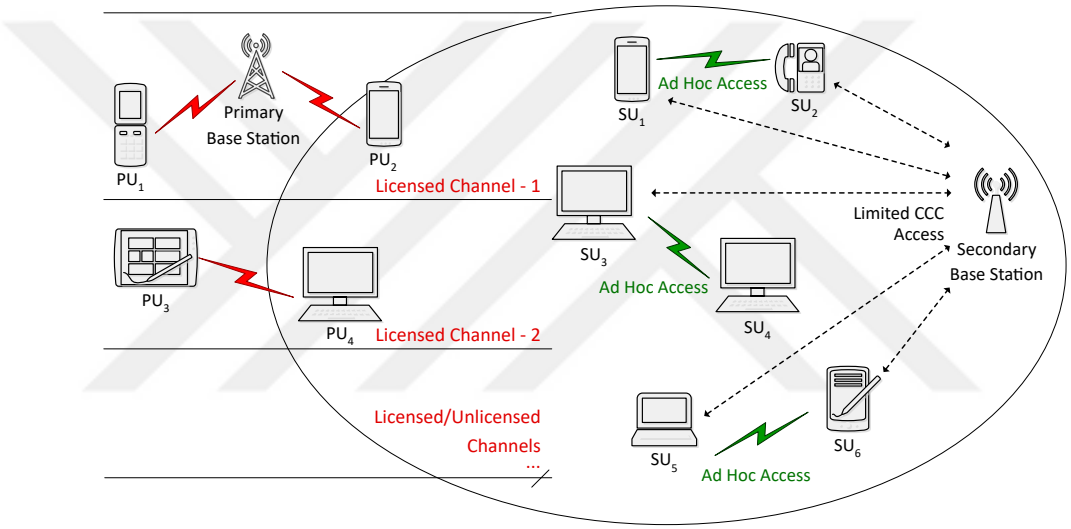


Figure 3.7 : Network system architecture.

A channel in *heavy use* is given as having duty cycle D_{heavy} and a channel in *sparse use* is given as having duty cycle D_{sparse}. The duty cycles of these PU channels are assigned using the middle of the decision intervals not to favor PU classification module in any direction. For modeling various network setups for multi-channel environment in a controllable manner, all PU channels were varied to have different but constant temporal behaviors (i.e. all channels are either in *heavy* or in *sparse use*, with the same μ_{ON} and μ_{OFF} throughout the simulation time). A simulation parameter was introduced named *Ratio of Heavy Channels*, that is defined as the ratio of number of heavily used channels over the number of all channels, denoted as R_{heavy} and formulated with (3.3).

$$R_{heavy} = \frac{M_{heavy}}{M} \text{ where } M_{heavy} = M - M_{sparse} \tag{3.3}$$

The parameters used in the network model are extended from the ones listed in Table 3.1 and the additional parameters along with their notations can be seen in Table 3.4.

Table 3.4 : Model parameters and notations specified for multi-channel environments.

Notation	Explanation
M	Number of total PU channels in the multi-channel environment
M_{sparse}	Number of PU channels in *sparse use*
M_{heavy}	Number of PU channels in *heavy use*
R_{heavy}	Ratio of PU channels in *heavy use*
D_{sparse}	Duty cycle of a sparsely used PU channel
D_{heavy}	Duty cycle of a heavily used PU channel
N	Number of SU users (transmitter SUs)

3.2.2 The proposed packet selection method

The packet selection strategy described in Section 3.1.3 that benefits from previously described heuristics provide the basis for the spectrum assignment algorithm, suited for multi-channel multi-interface environments including M PU channels.

The modified packet selection algorithm can be seen from Algorithm 2. Previously defined channel selection motivation and methods are employed for each available channel. The output binary decision vector's related field is filled considering available channels temporal status. The two output binary vectors are mutually exclusive as only a single packet (HP or LP packet) can be sent over a single channel at a decision instance. As the selected channels will be used in parallel by the SU, the queue size is also monitored not to result in an unnecessary channel selection upon queue exhaustion.

A simple demonstration of the channel selection algorithm can be seen in Figure 3.8, in which the histogram of the selected channels for each of two SUs are given. For both SUs, as seen in both Figure 3.8(a) and Figure 3.8(b), HP packets are sent from sparse channels, namely C_9 for SU_1 and C_{10} for SU_2, whereas the LP packets are sent from heavily used channels, namely: $\{C_1, C_3, C_5, C_7\}$ for SU_1 and $\{C_2, C_4, C_6, C_8\}$ for SU_2. This figure also visualizes the separation of available channels among the two

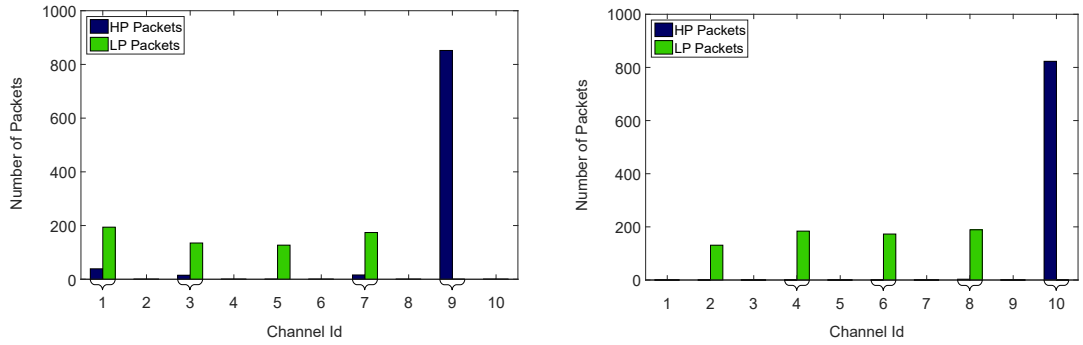
Algorithm 2
SU Packet Selection Algorithm in Multi-channel Environment

Require: Current binary spectrum sensing results for M channels: $x_{1,2,...,M}{}^t$,
Current integer PU classification results for M channels: $c_{1,2,...,M}{}^t$
(c_i^t : 1: *sparse use*, 2: *moderate use*, 3: *heavy use*),
Current SU Queue Sizes: $q_{hp}{}^t$, $q_{lp}{}^t$.

$send_{hp}{}^t \leftarrow [0,0,...,0]$ ▶ Binary decision vector for sending hp on each channel ($\left|send_{hp}{}^t\right| = M$)
$send_{lp}{}^t \leftarrow [0,0,...,0]$ ▶ Binary decision vector for sending lp on each channel ($\left|send_{lp}{}^t\right| = M$)
$q_{hp\_next}{}^t \leftarrow q_{hp}{}^t$ ▶ Keep current queue size for HP traffic
$q_{lp\_next}{}^t \leftarrow q_{lp}{}^t$ ▶ Keep current queue size for LP traffic

for each channel $i \in \{1,2,...,M\}$ **do**
  if $x_i^t = 0$ **then**
    if $c_i^t = 1$ **then** ▶ Channel classified as in *sparse use*
      if $q_{hp\_next}{}^t > 0$ **then** ▶ Favor HP traffic
        $send_{hp}{}^t \leftarrow 1$
        $q_{hp\_next}{}^t \leftarrow q_{hp\_next}{}^t - 1$
      else if $q_{lp\_next}{}^t > 0$ **then**
        $send_{lp}{}^t \leftarrow 1$
        $q_{lp\_next}{}^t \leftarrow q_{lp\_next}{}^t - 1$
      end if
    end if
    if $c^t = 2$ **then** ▶ Channel classified as in *moderate use*
      if $q_{hp\_next}{}^t > 0$ **and** $q_{hp\_next}{}^t > q_{lp\_next}{}^t$ **then** ▶ Select greater queue size
        $send_{hp}{}^t \leftarrow 1$
        $q_{hp\_next}{}^t \leftarrow q_{hp\_next}{}^t - 1$
      else if $q_{lp\_next}{}^t > 0$ **then**
        $send_{lp}{}^t \leftarrow 1$
        $q_{lp\_next}{}^t \leftarrow q_{lp\_next}{}^t - 1$
      end if
      if $q_{lp\_next}{}^t > 0$ **and** $q_{lp\_next}{}^t > q_{hp\_next}{}^t$ **then**
        $send_{lp}{}^t \leftarrow 1$
        $q_{lp\_next}{}^t \leftarrow q_{lp\_next}{}^t - 1$
      else if $q_{hp} > 0$ **then**
        $send_{hp}{}^t \leftarrow 1$
        $q_{hp\_next}{}^t \leftarrow q_{hp\_next}{}^t - 1$
      end if
    end if
    if $c^t = 3$ **then** ▶ Channel classified as in *heavy use*
      if $q_{lp}{}^t > 0$ **then** ▶ Favor LP traffic
        $send_{lp}{}^t \leftarrow 1$
        $q_{lp\_next}{}^t \leftarrow q_{lp\_next}{}^t - 1$
      else if $q_{hp\_next}{}^t > 0$ **then**
        $send_{hp}{}^t \leftarrow 1$
        $q_{hp\_next}{}^t \leftarrow q_{hp\_next}{}^t - 1$
      end if
    end if
  end if
end for
return $send_{hp}{}^t, send_{lp}{}^t$

SUs. The SUs use disjoint channel sets as a result of scheduling method that will be detailed in next section.



(a) Channel distribution for SU_1.

(b) Channel distribution for SU_2.

Figure 3.8 : Used channel distributions for multi-channel spectrum assignment algorithm coupled by spectrum sharing technique (Sample distribution simulation parameters: $R_{heavy} = 0.8$ with heavily used channels: $\{C_1, \cdots, C_8\}$ and the sparsely used channels: $\{C_9, C_{10}\}$).

3.2.3 The proposed distributed scheduling method

For a more realistic DSA network model including multiple channels and multiple SUs in a single collision domain, a scheduling solution is also developed in parallel to the packet selection algorithm described above. The proposed scheduling mechanism is a simple and a fast distributed method that achieves collision-free scheduling among all SUs, that also establishes load balancing implicitly. Moreover, proposed scheduling method do not use a CCC at each scheduling period unlike most of the existing MAC protocol studies.

It is inspired from the rendezvous problem in CRNs, for which a vast portion of existing research proposes solutions using channel hopping techniques and variety of modulus operations like in [78] and [79]. In contrast to the rendezvous problems, of which the main aim is to try to schedule two SUs at same channel at the same time, the proposed solution does the opposite (i.e.never schedules any two SU to the same channel at the same time slot). Each SU employs a channel selection mechanism inspired from periodic channel hopping method. However, this method is not an actual hopping operation in which SUs select/hop the channels sequentially in time. Instead, the channel-hopping-like operation is used to construct a set of channels that each SU can utilize. These selected channels are then used in parallel at the same time slot.

The proposed channel selection mechanism selects a channel set for specific user, regardless of availability of channels and the channel temporal behavior. SUs will perform spectrum sensing and will decide which channels to use for which packets.

Specifically, the proposed scheduling is coupled into Algorithm 2, producing a set of usable channels, denoted by M', instead of M channels at the outer channel loop seen in line number 10. The set of usable channels is determined particularly by property: $Channel_m$ $(1 \leq m \leq M)$ will be selected by SU_i $(1 \leq i \leq N)$ by below condition:

The proposed distributed scheduling mechanism allows each SU to select a subset of channels to use with the property: $Channel_m$ $(1 \leq m \leq M)$ will be selected by SU_i $(1 \leq i \leq N)$ by below condition:

$$i = (m-1)_{mod_N} + 1 \tag{3.4}$$

where M refers to the number of PU channels in the network and N is the total number of SUs.

Theorem 1. *SU channel scheduling with the proposed channel selection:* $Channel_m$ $(1 \leq m \leq M)$ *will be selected by* SU_i $(1 \leq i \leq N)$ *with given constraint in* (3.4) *provides a conflict-free scheduling.*

Proof. (by contradiction) Suppose proposed channel selection does not provide a conflict-free scheduling i.e: Arbitrary $Channel_m$ is selected by two or more SUs e.g. SU_i and SU_j $(i \neq j)$. The channel selection constraint given in (3.4) should hold both of them. Next, this constraint can be expanded for both of them as follows:

$$\begin{aligned} (m-1)_{mod_N} + 1 &= i \\ (m-1)_{mod_N} &= i-1 \\ m-1 &= (i-1) + c_i * N \\ m &= i + c_i * N \end{aligned} \quad \Bigg| \quad \begin{aligned} (m-1)_{mod_N} + 1 &= j \\ (m-1)_{mod_N} &= j-1 \\ m-1 &= (j-1) + c_j * N \\ m &= j + c_j * N \end{aligned}$$

$$\begin{aligned} i + c_i * N &= j + c_j * N \\ i - j &= (c_j - c_i) * N \end{aligned}$$

$$\text{Given: } 1 \leq i, j \leq N \Rightarrow 0 \leq i - j \leq N - 1$$

$$\begin{aligned} c_i = c_j &= 0 \\ i &= j \end{aligned}$$

contradicting with the initial assumption of $i \neq j$. □

Figure 3.9 demonstrates the scheduling mechanism for all SUs in the network. First row in the figure illustrates all channels in the system, whereas the last row

demonstrates the id of the SU that can utilize each channel. As each SU will employ the same selection principle based on (3.4), the owner of a specific channel would have been decided deterministically and in a distributed way. Moreover, any collision is prevented as can be seen from the proof of Theorem 1. One of the main advantages for the proposed scheduling scheme is that, by design, there is no need for synchronization among contending SUs, considering phase shifts of SUs are not important when they are accessing disjoint channel sets. Moreover, since each SU uses its own spectrum sensing results in its channel prediction operation and acting on its behalf, there is no need for synchronization at the spectrum decision phase as well.

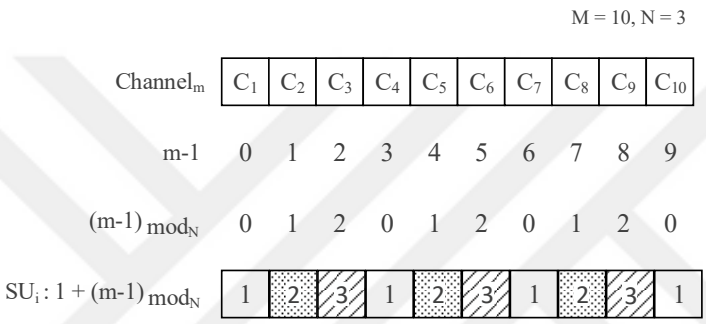


Figure 3.9 : Spectrum scheduling method for distributed SUs.

By the designed selection principle on each SU, the channel distribution among these SUs provides fairness at the most achievable manner. Obviously when the number of channels is not an exact multiple of the number of SUs (like the example seen in Figure 3.9), there will exist one or more SUs like SU_1 in Figure 3.9 that will take one more channel than the others.

In Section 3.2.4, where the performance of the proposed methods are studied in multi-channel environments, the proposed scheduling scheme is benchmarked with the *"Random Scheduling"* method in which the SUs select $N_c = M'/N$ channels randomly from the available channel set, where M' is the number of available PU channels. To observe solely the performance of the proposed distributed scheduling scheme with respect to varying number of SUs, the scheduling module is separated out from the designed MATLAB® model, and its standalone behavior is simulated. The proposed scheduling method is an eminently protective approach that prevents collisions among SUs. Therefore the number of SUs has no effect on the network utilization. Also the

effect of increasing number of SUs on the *throughput ratio* for benchmarked random scheduling scheme is analytically formulated as follows.

In random scheduling, each SU selects randomly N_c channels from M' channels, referring to a combination of $C(M', N_c)$. Probability that a channel (e.g. C_m) is selected by SU_i in his generated combination can be given as in Equation 3.5.

$$\begin{aligned} Pr\{C_m \in C(M', N_c)\} &= \frac{C(M'-1, N_c-1)}{C(M', N_c)} \\ &= \frac{N_c}{M'} = \frac{\frac{M'}{N}}{M'} = \frac{1}{N} \end{aligned} \tag{3.5}$$

Channel throughput is dependent on the number of SUs that selected the channel (denoted by k) and can be defined by Equation 3.6. Successful data transmission on a specific channel (e.g. C_m) occurs only if it is selected by exactly one SU. All other cases result with either a missed transmission opportunity (none of the SUs select the channel) or a collision (more than one SU select the same channel). Thus, the channel throughput is expressed as:

$$T_m(k) = \begin{cases} 1 & k = 1 \\ 0 & otherwise \end{cases} \tag{3.6}$$

In terms of network throughput, the probability for each channel to be selected by exactly one SU has to be investigated. This probability will have a binomial distribution with the following parameters: the number of independent experiments which is denoted by $n = N$ (as there would be N channel sets/combinations selected by N SUs), success probability defined with Equation 3.5, denoted by $p = 1/N$, and the number of successful trials of interest, denoted by $k = 1$. Therefore, the probability that a channel has unit throughput in a multi-user environment is formulated as in Equation 3.7.

$$f(1; N, \frac{1}{N}) = \binom{N}{1} \left(\frac{1}{N}\right)^1 \left(1 - \frac{1}{N}\right)^{N-1} = \left(1 - \frac{1}{N}\right)^{N-1} \tag{3.7}$$

Using Equation 3.6 and Equation 3.7, the expected throughput of single channel in multi-user environment is formulated as below:

$$E[T_m] = \sum_{k=0}^{N} T_m(k) f(k) = T_m(1) f(1) = \left(1 - \frac{1}{N}\right)^{N-1} \tag{3.8}$$

As the selection of each channel is independent from each other, using Equation 3.8, expected total network throughput of M' idle channels in system becomes $M'(1-(1/N))^{N-1}$. The *Throughput Utilization* is also defined as the ratio between the expected or the observed total throughput over total available throughput, that analytically becomes $(1-(1/N))^{N-1}$. From Figure 3.10, the analytical and the simulation results for varying number of SUs as $N = \{1,2,3,4,6,8,12,24\}$ and $M' = 24$ can be seen. The throughput utilization for the proposed scheduling scheme is 1 in each case, considering that the method does not schedule more than one SU in any channel, as given by proof of Theorem 1. It is also seen in Figure 3.10 that the modified random scheduling method is highly effected by the number of SUs and the throughput utilization therefore decreases with increasing number of SUs whereas the proposed method's performance is independent of N.

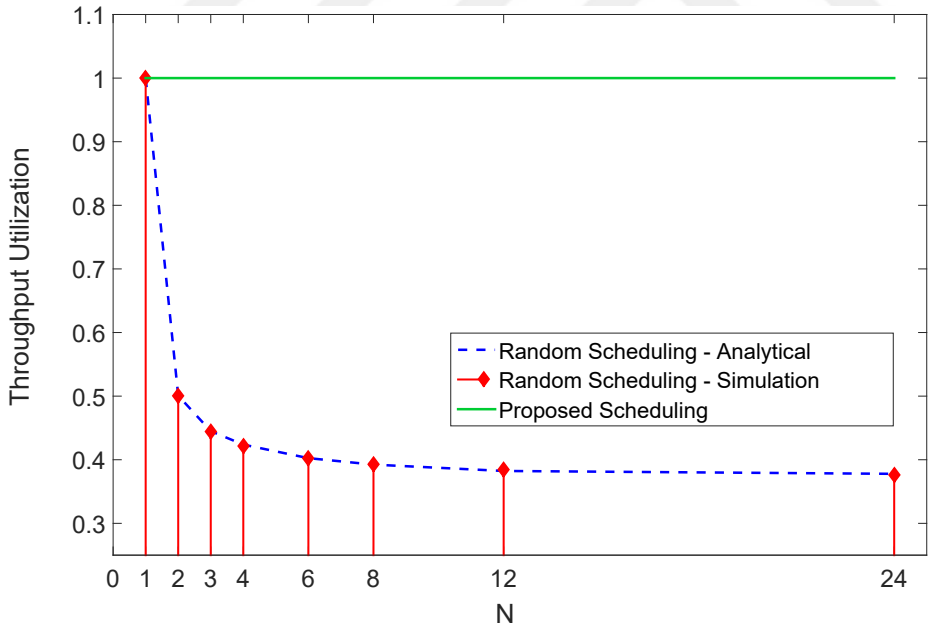


Figure 3.10 : Throughput utilization

The drawback of the proposed spectrum sharing mechanism may arise from the fact that the channel would be reserved for an SU, even though the user has no data to send. Like many existing works, it is natural to assume the SUs has always data to send, as they are frequently preempted by PUs. This assumption is valid especially in the use case that is considered in the network model used in this thesis, where SUs

have high traffic demands in several queues at several QoS levels. Non-existence of any data in SU transmission queue is less likely to happen in the model, but can easily be eliminated by the introduction of cooperation among the distributed SUs that may permit channel borrowing among neighboring SUs. More complex further cooperativeness among SUs, may also increase overall utility. However, this approach should not converge to a scheme like centralized solution by use of extensive messaging. Therefore, a simpler, fully distributed scheduling approach is deployed.

The only information that has to be disseminated among SUs for the proposed protocol is the number of channels and the number of SUs in the system. Upon any topology change, a newly added SU or a leaving SU information will be broadcast to all SUs. This broadcast will be achieved by the Secondary Base Station (SBS) using the limited Common Control Channel (CCC) connectivity in the network architecture as seen in Figure 3.7. Leaving or newly added SUs can advertise themselves when the CCC is maintained with the SBS, and the SBS then, can disseminate this information down to connected SUs again from the CCC. Similarly, the primary channel set can be broadcasted to all SUs in the system for initial setup and the SBS can track changes in the number of channels independently. A reduction in the number of the primary channels is very exceptional, but to detect such a change, the SBS can continuously sense PU channels and decide to remove a channel after a considerably long time of unavailability. Addition of a primary channel can be explicitly introduced to the SBS, that will also require a broadcast to all SUs if the channel could also be sensed by all of them. As the recurrence of these network events which requires a broadcast, will be much less frequent than the CCC usage frequency of a regular centralized solution or MAC protocols for all control messaging (e.g. at each spectrum sensing period), proposed schemes still avoid centralized solution problems, like maintenance of the CCC.

In Figure 3.8, previously given in Section 3.2.2, the channel distribution of the successfully transmitted packets for both SUs are also seen. SU_1 uses channels: $\{C_1, C_3, C_5, C_7, C_9\}$ as seen in Figure 3.8(a). Considering $N = 2$, with the described scheduling mechanism, SU_2 is then supposed to use even numbered channels that can also be observed from Figure 3.8(b).

3.2.4 Evaluation of the proposed methods

In this section, the proposed channel assignment algorithms coupled with spectrum sharing mechanisms are evaluated for various environments. All channel selection and spectrum sharing methods are implemented on top of a detailed MATLAB Simulink® model. Components of SimEvents® are used for the queuing mechanisms. Several simulations for the demonstration of the performance of the proposed algorithm are performed using the designed model.

The proposed spectrum assignment method was compared with the *"Native Scheme"* in the single-channel-single-user environments in Section 3.1.4 that leverages HP packets in all available channels. As a distributed scheduling mechanism is proposed to couple with the proposed spectrum assignment algorithm, it is compared with *"Random Scheduling"* in which SUs select channels randomly from the available channel set. The number of channels each SU will select in the random selection method would highly effect the overall performance as it directly correlates with the probability of collision among all contending SUs. In the modified random scheduling mechanism that we implemented for our performance comparisons, each SU selects N_c number of channels such that $N_c = M'/N$ where M' is the number of available PU channels. This approach reflects a principle of each SU using his share of the spectrum availability and select his portion randomly. Accordingly, the combination of the spectrum assignment and scheduling steps resulted in four different versions labeled in Figure 3.11 as follows:

- *"Proposed Channel Selection & Proposed Scheduling"*: SU initially determines its usable channel set by using the distributed scheduling algorithm, then selects a packet from one of his QoS discriminated queues with respect to the temporal behavior of each channel, using proposed spectrum assignment algorithm.

- *"Proposed Channel Selection & Random Scheduling"*: SU initially determines its usable channel set from the available channel set, randomly, then selects a packet from one of his QoS discriminated queues with respect to the temporal behavior of each channel, using proposed spectrum assignment algorithm.

- *"Native Channel Selection & Proposed Scheduling"*: SU initially determines its usable channel set by using the distributed scheduling algorithm, then selects HP

packets on every spectrum opportunity, unless HP queue becomes empty; if so, selects LP packets.

- *"Native Channel Selection & Random Scheduling"*: SU initially determines its usable channel set from the available channel set, randomly, then selects HP packets on every spectrum opportunity, unless HP queue becomes empty; if so, selects LP packets.

The multi-channel spectrum assignment and the scheduling mechanisms are simulated using the parameters given in Table 3.5. The time dependent parameters like μ_{ON}, μ_{OFF}, τ_{delay}, T_H, T_L, T_{SIM} and t_s are given in unit of a single step of discrete event simulator of MATLAB Simulink®. In these set of simulations, the network model consists of N SUs and N receivers (without a relay node in between) exposing same set of PU channels.

Table 3.5 : Parameters for the multi-channel environment simulations.

Notation	**Value/s**
M	10
N	2
R_{heavy}	$\{0.0, 0.1, 0.2, 0.3, 0.4, 0.5$ $0.6, 0.7, 0.8, 0.9, 1.0\}$
D_{heavy}	0.84
D_{sparse}	0.16
μ_{OFF}	4
τ_{delay}	10
$\|Q_{HP}\|$	inf
$\|Q_{LP}\|$	inf
$\|W_H\|$	100
T_H	0.1
T_L	0.4
T_{SIM}	1000
t_s	1
k	$\{1.0, 1.1, 1.2, 1.3, 1.4, 1.5,$ $1.6, 1.7, 1.8, 1.9, 2.0\}$

Average FoM over individual FoMs of each SUs is illustrated in performance plots. 10 runs were averaged for each setup and results were given within 95% confidence intervals.

In Figure 3.11, the FoM values are depicted for $k = 2$. As expected, within the the four versions of the methods, the worst performance belongs to the *"Native*

Channel Selection & Random Scheduling" method. It is seen that the dominant feature is the scheduling rather than the channel selection, as the effect of the scheduling method can be observed at every heavy channel ratio, whereas the proposed spectrum channel selection is advantageous mostly in higher heavy channel ratios. The proposed distributed scheduling outperformed the modified random scheduling.

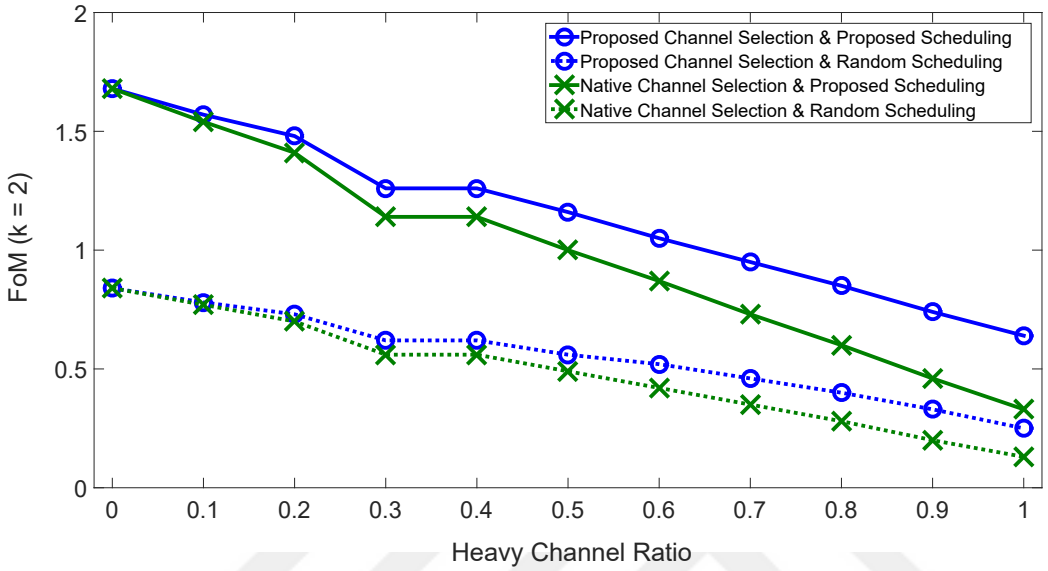


Figure 3.11 : Figure of Merit for $k = 2$ (multi channel environment).

The FoM for various k values are plotted in Figure 3.12 for the *"Proposed Channel Selection & Proposed Scheduling"* and *"Native Channel Selection & Random Scheduling"* schemes.

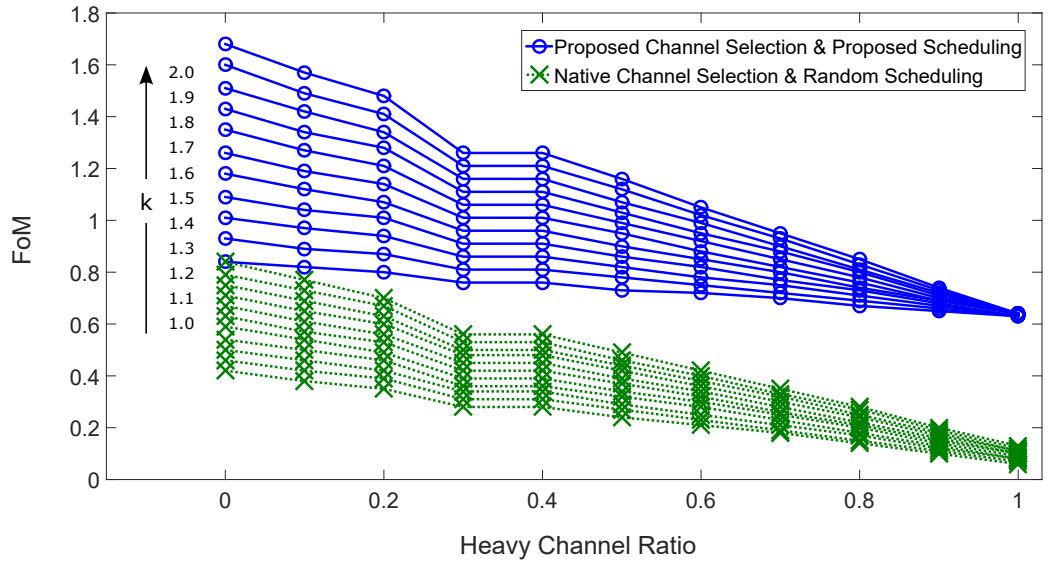


Figure 3.12 : Figure of Merit for various k values (multi-channel environment)

The general trend of FoM decrease as the number of heavily used channels increase can be observed. In Figure 3.11, the decrease of the effect of k parameter can also be seen as R_{heavy} increases, reflecting a similar phenomenon seen in the single-channel environment simulations, previously illustrated in Figure 3.3. As the proposed scheme is biased to take LP packets on channels classified as in *heavy use*, the transmission of HP packets becomes limited with increasing ratio of heavy channels, making the effect of k parameter less dominating.

4. PROPOSED FRAME-TYPE-DIFFERENTIATED QUEUE MANAGEMENT METHOD FOR VIDEO TRANSMISSION OVER COGNITIVE RADIO NETWORKS

In this chapter, a distributed queue management scheme is proposed and evaluated that uses the frame type information inside the video packets to be transmitted, and provides a smarter protection against a probable packet loss that results from the dynamic nature of the SU spectrum availability. Detailed information about the design of the proposed mechanisms, the employed cognitive radio network model and the obtained results from the performance evaluations are presented in the following sub-sections.

Previously developed multi-channel channel selection algorithm described in Section 3.2 was based on performing a discrimination among high priority and low priority packets. In the network model used in this chapter, where a video transmission is employed, the discrimination will take place among different video frames within the encoded video burst. Therefore, the scheduling scheme described in this section acts like an inner queue management scheme inside the high priority packets queue. More heterogeneous service classes can also be defined including best effort and several other low and high prioritized traffic types along with an encoded video transmission. However, in order to observe algorithm's direct effect on the received video quality at the receiver, the video transmission is solely focused.

Section 4.1 presents the video encoding standard used in the model and the proposed scheme. The network model is described in detail in Section 4.2 and the designed queue management method is introduced in Section 4.3. Section 4.4 includes the performance evaluation of the proposed method in terms of several perceptual visual quality metrics.

4.1 Video Encoding

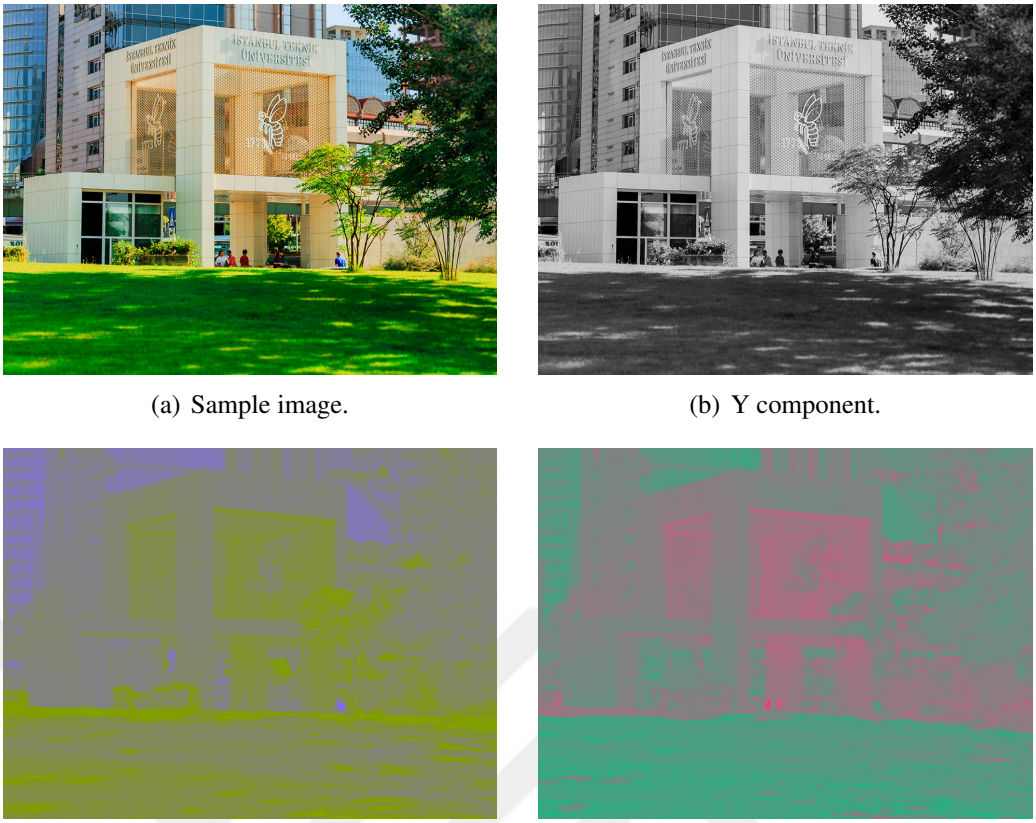
MPEG-2 (aka H.222/H.262 as defined by the ITU) encoding is used in the proposed methods. MPEG-2 is a video coding standard created by the Moving Picture Experts Group (MPEG) and finalized in 1994. MPEG-2 uses three frame types (I, P, and B) to represent the video. A *Group of Pictures (GOP)* setting defines the pattern of the three frame types used [80].

Color model: Coding a frame in MPEG-2 format always begins by representing the original color frame in YCbCr format. The Y component represents the luminance, while Cb and Cr components represent chrominance differences for blue and red colors, respectively. The three components of this color model are mostly uncorrelated, so this transformation is a useful first step in reducing redundant information in the frame [81]. Chroma sub-sampling method, described in next item, achieve this reduction. Figure 4.1 visualizes the YCbCr color space components of the sample image. Figures 4.1(a) and 4.1(b) visualize the raw image and its Y component. The blue chrominance difference (Cb component) is seen in Figure 4.1(c) and the red chrominance difference (Cr component) is seen in Figure 4.1(d).

Chroma sub-sampling: An intelligent way to reduce the amount of information to be encoded is by taking advantage of human visual perception properties. Human eyes are much more sensitive to variations in brightness than color, so it is common to keep the luminance channel as broad as possible and sub-sample both chrominance channels for data reduction.

Chroma sub-sampling formats are denoted with a triplet in form of J:a:b. The first component represents the number of pixels in the considered region. This region has a dimension of $2xJ$ and J is set to 4 in existing standards. a is the number of chrominance samples in the first row of J. b is the number of changes in the chrominance samples for the second row of J. The b component of the triplet can be either 0, reflecting that no new chrominance samples will be taken from the second row, or can be equal to a meaning that the second row will also be chroma-sampled with the same ratio as the first row.

Figure 4.2 includes a demonstration of several chroma sub-sampling formats. In Figure 4.2(a), the effect of a and b can be observed. When a equals b, like the cases in



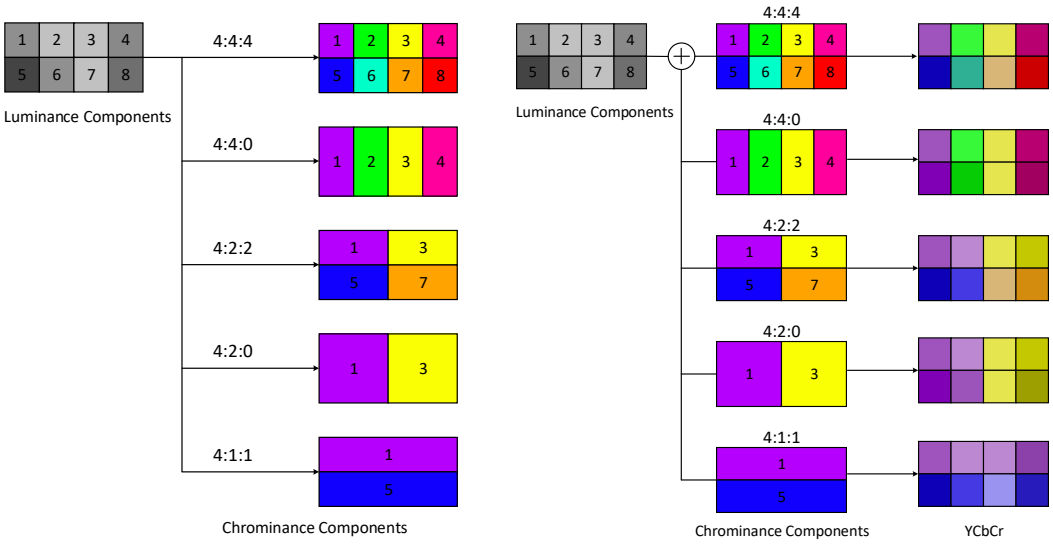
(a) Sample image. (b) Y component.

(c) Cb component. (d) Cr component.

Figure 4.1 : YCbCr components of the sample image.

4:4:4, 4:2:2 and 4:1:1, the second row pixels are chroma sub-sampled independently of the first row, resulting in different colors. When b equals to 0, like the cases in 4:4:0 and 4:2:0, the second row does not contain any new chroma information and the information from above row is used. The numbers in Figure 4.2(a) are used as an identifier for chrominance components of the pixels in the considered region. While, the raw data has 8 different chrominance components, after the sub-sampling is applied, the total number of used chrominance information may drop down to 2 like in 4:1:1. The most commonly used sub-sampling format is denoted by 4:2:0, which means that chrominance sampling is decimated by 2. In this way, both chrominance channels are reduced to one quarter the original data rate and the net effect is that the data rate to be cut in half with hardly any perceptual effect on image quality [81]. Resulting images after merging the chroma sub-sampled chroma components and the luminance component can also be seen in Figure 4.2(b).

In the presented simulations within this thesis, no chroma sub-sampling reduction is performed and the luminance channels are used alone.



(a) Chroma sub-sampling variants. (b) Resulting chroma sub-sampled images.

Figure 4.2 : Chroma sub-sampling demonstration.

Block based coding: MPEG-2 uses block based coding such that a frame is divided into many independently coded blocks. A *macro-block* is 16x16 pixels and is a basic unit of MPEG-2 coding that is further divided into 8x8 pixel *block*s.

Figure 4.3 visualizes the block based coding principles where one can see that each *Group of Pictures (GOP)* contains several *Pictures/Frames* that are divided into *Slices* and each slide contains several macro-blocks that are basic coding units.

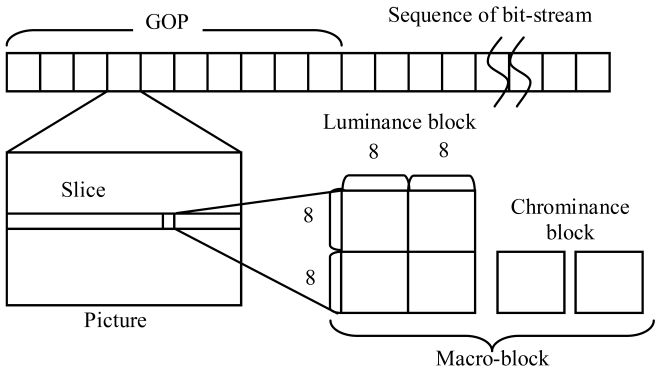


Figure 4.3 : Block based coding used in MPEG-2 [6].

I frame coding: An I frame is intra or spatially coded so that all the information necessary to reconstruct it is encoded within that frame's segment of the MPEG-2 bit stream. It is a self contained image compressed in a manner similar to a JPEG image.

P frame coding: A P frame is inter or temporally coded. That means it uses correlation between the current frame and a past frame to achieve compression. The MPEG-2 standard dictates that the past frame must be an I or P frame, but not a B frame. P frames are *predicted* based on prior I or P frames plus the addition of data for changed macro-blocks.

Both I-frames and P-frames are also known as *reference* frames, because a B-frame may refer to either one or both frame types.

B frame coding: A B frame is simply a more general version of a P frame. B frames are *bidirectionally* predicted frames based on appearance and positions of past and future frames macro-blocks. Motion vectors can refer not only to a past frame, but to a future frame, or both a past and future frame. Using future frames is exactly like a P frame except for referencing the future. Using past and future frames together works by averaging the predicted past macro-block with the predicted future macro-block. The residual is coded like a P frame in either case. B frame encoding provides advantage of high compression ratio along with increased decoding complexity and delay.

The encoding relations between I, B and P frames are demonstrated in Figure 4.4. The sample scene in Figure 4.4 includes a car passing by in front of a nature view background. This is a typical case where a bidirectional reference is necessary due to object occlusion. The I frame is first encoded using the original frame (Frame 1 in Figure 4.4). In the encoding order, next, the P frame is encoded using both the original and the encoded I frames (demonstrated by the arrows 2 and 3 in Figure 4.4). The unchanged background information is available directly from the previous I frame and the movement information of the car is stored in motion vectors (MV1 in in Figure 4.4). B frame is then encoded after the P frame using both of the previously encoded reference I and P frames (demonstrated by the arrows 24 and 5 in Figure 4.4). The motion vectors used in the B frame encoding (MV2 in Figure 4.4) capture the movement of the car in the scene, however, the background information of the car's previous location (marked with gray in Frame 2 in Figure 4.4) cannot be gathered from the previous reference frame. As the P frame is temporally latter than the B frame, it contains the required background information. B frame encoding uses this latter frame information and provides opportunity of increased compression ratio by using reference frames in both directions.

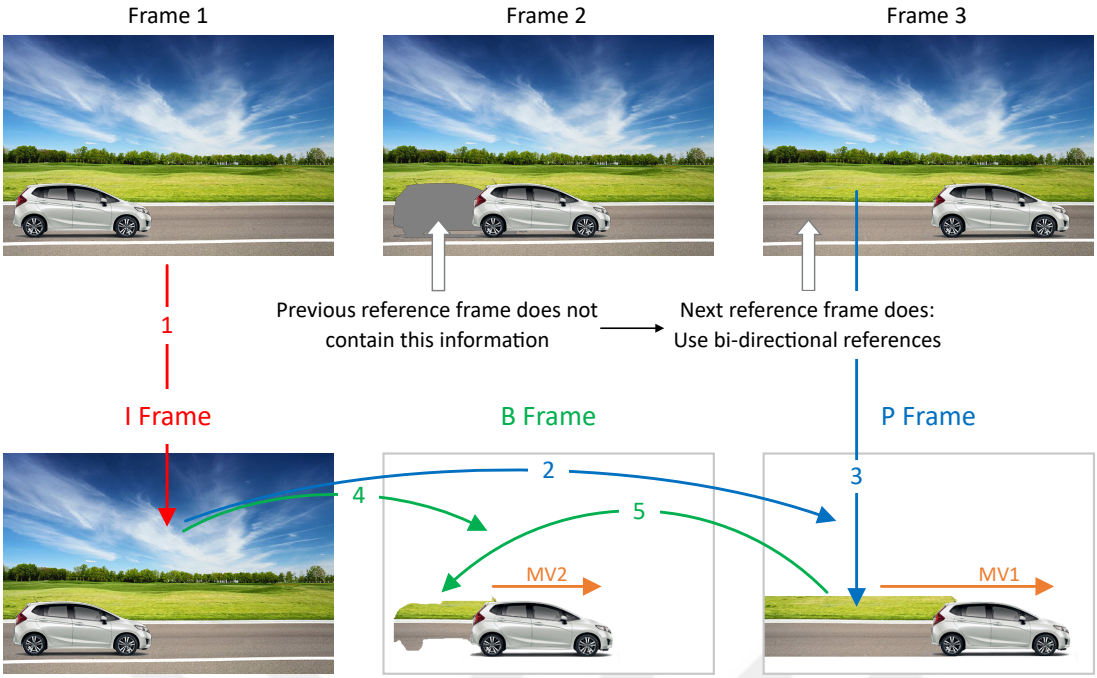


Figure 4.4 : Sample I, B and P frames.

The ordering of I, P, and B frames is fairly flexible in MPEG-2. The first frame must always be an I frame because there is no other data for a P or B frame to reference. After that, I, P, and B frames can be mixed in any order. The P frames reference the last I or P frame and the B frames reference the closest past and future I or P frames. I, B and P frames are enclosed in GOP structure.

A GOP begins with an I frame, followed usually by a number of P and B frames. In an open GOP model, an I frame and the successive frames up to the next I frame is known as a GOP. In a closed GOP model, GOP again starts with an I frame but ends with a P or a B frame. In a closed GOP model, each GOP is independent, that is, all frames needed for the predictions are contained within the same GOP, whereas in an open GOP model, the last frame in a GOP references an I frame of the next GOP. A GOP can be as small as a single I frame, or as large as desired, but usually no more than 15 frames in length.

Each video burst in the network model used is assumed to be encoded using the MPEG-2 with a specified GOP pattern. In the network model, 15 frame open GOP structure with a pattern parameter, denoted by b_f, as the number of B frames between the reference frames (i.e. I and P) set to 2. Described GOP pattern and its frame dependencies can be seen in Figure 4.5.

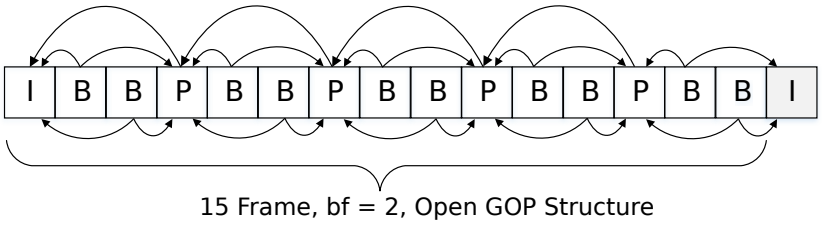


Figure 4.5 : Open GOP structure and frame dependencies.

Here, it has to be noted that MPEG-2 encoding is used for a more controlled packet structure and an environment for solely analyzing the effect of the queue arrangement scheme. However, the proposed approach can also be applied to other encoding standards like Scalable Video Coding (SVC) [63]. SVC extension of the H.264/AVC standard can provide significant benefits for CR applications due to its temporal, spatial, and quality scalability that enables on-the-fly codec re-configuration based on video quality, required resolution at the terminal, and channel conditions.

4.2 Network Model

The employed network model consists of a single SU transmitter node that forwards the video packets to an SU receiver node in a cognitive manner over M PU channels.

The transmitter SU samples the continuous PU traffic at every channel simultaneously and decides their status accordingly. The spectrum sensing operation is assumed to be completed instantaneously at the beginning of each sampling period (t_s), and the PU status is assumed to be stationary during t_s. The transmitter SU is allowed to transmit only when the spectrum sensing detects a PU vacancy. In designed model, without the loss of generality, it is assumed that an SU can process and send one packet throughout single t_s. The PU traffic at each channel is modeled to have a Poisson distribution such that the mean of the exponentially distributed active and inactive periods are μ_{ON} and μ_{OFF}, respectively.

Video traffic requests at the sender SU are modeled to arrive in bursts, and the corresponding video packets for each burst are placed in transmission queue at the same time. A time-out mechanism for these video packets is also employed reflecting their reneging behavior: a video packet is dropped when its waiting time exceeds a

predefined threshold value denoted by τ_{delay}. This mechanism provides an upper bound on waiting time to the receiver SU before it starts processing its receive buffer.

4.3 The Proposed Queue Management Scheme

The operations performed in the transmitter and the receiver SUs are visualized in Figure 4.6. After the MPEG-2 encoding step, video frames are bundled into video packets with similar sizes. Each packet can carry N_I number of I, N_P number of P or N_B number of B frames. In [82], the relative sizes of P and B frames with respect to an I frame is given in a wide range of intervals according to the video content. The size of an I frame changes from 1.25 to 6 times of a P frame and 2.5 to 24 times of a B frame, where the ratio increases with decreased motion component. In mixed-motion type videos, it has been observed that the ratio can be assumed as 3 and 7 for P and B frames, respectively, which is in accordance with the numbers given in [82]. It has to be noted that the designed model is an abstract one, and a similar aggregation can be incorporated into any network simulator where the MPEG-2 frames are bundled into IP packets in the form of *MPEG-2 Transport Service* packets.

For each video burst, the transmitter SU places the video packets into its transmission queue randomly to ensure the potential packet loss will be randomly distributed. The proposed queue management scheme places the I and the P packets to the top of the queue in random order so that they are transmitted before the B packets, which are also placed in random order within themselves.

The receiver SU re-sequences the received video packets in its receive buffer and de-packetize them into MPEG-2 frames. The receiver SU then starts decoding of the video burst using received frames. No error concealment mechanism is employed in the model in order to measure solely the effect of the packet loss on the proposed queue management scheme. Therefore, the frames which are undecodable due to the loss of their packets or the loss of the packets carrying their dependent frame/s are left as a blank image in the performance calculations.

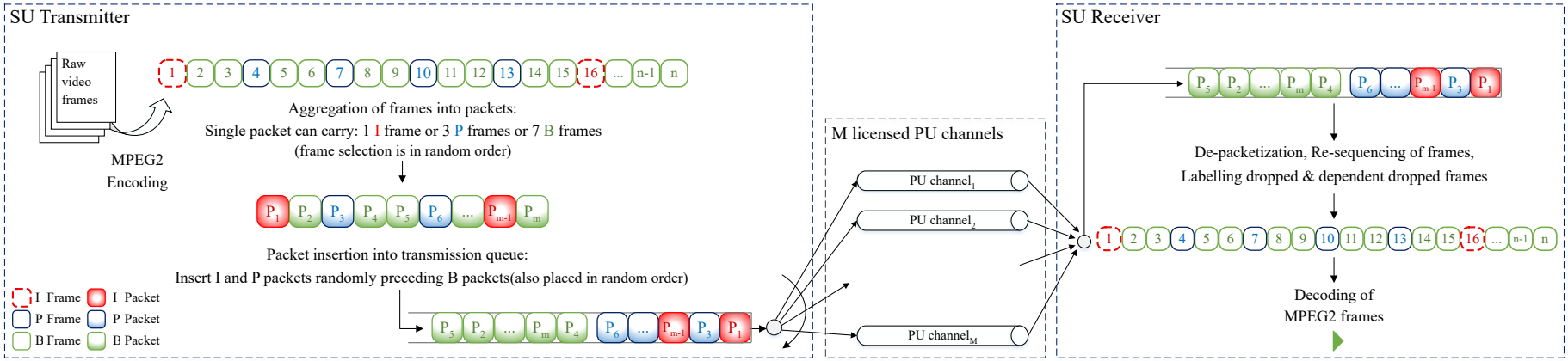


Figure 4.6 : SU video transfer model.

The motivation behind the proposed queue management scheme comes from the added value of I and P frames. Due to the frame encoding/decoding dependency relations within the GOP pattern, the loss of an I packet results with a loss of N_I number of I frames, each of which cause the loss of 16 other frames. Similarly the loss of a P packet results with a loss of N_P number of P frames, each of which will cause the loss of an additional 4, 7, 10 or 13 frames, depending on the position of each P frame inside their GOP. Unlike the loss of an I or a P packet, the loss of a B packet results with only the loss of N_B number of B frames and no other additional ones. In Section 4.4.2, the effect of these different packet loss variations are analyzed on the same spectrum availability environments, which supported initial motivations.

4.4 Evaluation of the Proposed Scheme

The performance of the proposed frame-type-differentiated queue management scheme is evaluated using the visual performance metrics: Peak Signal to Noise Ratio (PSNR-Y, see Appendix 6 for details of its calculation), Mean Structural SIMilarity (MSSIM-Y [72]), and Q, which is the decodable frame ratio over total number of frames. PSNR-Y performance can also be mapped into classes of an objective video quality metric, named Mean Opinion Score (MOS), in several references such as [72] and [83]. PSNR and MSSIM metrics are calculated using the Y (luminance) channel of the videos, represented as gray-scale images. Even if the MSSIM-Y performance measure is designed to improve the most commonly used PSNR-Y metric in terms of better reflection of human visual perception, it has to be noted that these performance metrics along with Q metric are highly correlated and the performance degradation is dominated with the variation in packet loss instead of the individual frame differentiations for very noisy environments like CRNs. Performance metrics measurements of the received and the original encoded video frames are performed as a post processing step for both the motivational and the model simulations.

The selected sample videos are listed in Table 4.1. The MPEG-2 encoding of these videos is accomplished using FFmpeg software [84], and the remaining steps are completed in MATLAB®. For both the motivational and the model simulations, after the lost packets are determined, received frames are re-sequenced and decoded. Undecodable frames are represented as black images. The performance comparison

is done per image basis between the original and the decoded video frames, and the average performance for whole video is calculated.

Table 4.1 : Properties of sample videos used in simulations [1].

Video Short Name	Resolution	Number of Frames	Action Type
Football	720 x 486	360	Motion
Washington DC	720 x 486	360	Mixed
Galleon	720 x 486	360	Steady

The performance evaluation flow can be seen in Figure 4.7. After the raw video encoding step, encoded frames are bundled into video packets that are then subjected to deterministic packet drop mechanism or transferred over the multi-channel CRN model. After the received video packets are de-packetized and re-sequenced, the lost frames are identified. Performance comparisons are carried out using the received and the raw video frames.

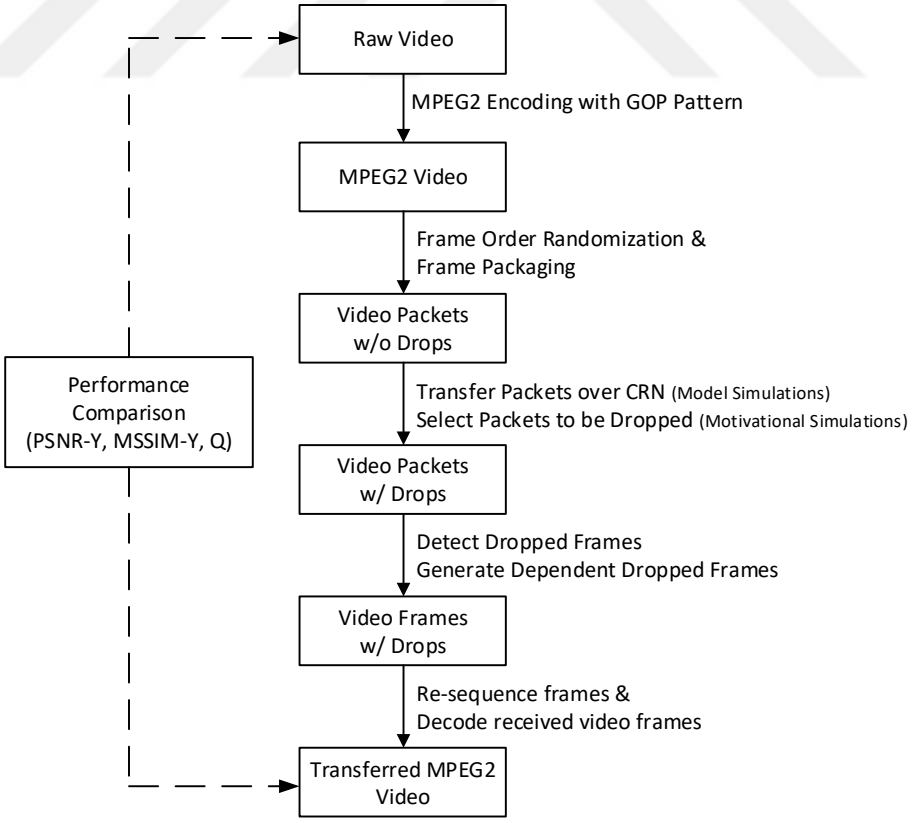


Figure 4.7 : Performance evaluation flow for the simulations.

The presented results in all figures represent the average of 50 runs with identical setup, except for the seed used in randomized PU traffic pattern. As observed from the resulting visual video quality metrics, the proposed scheme outperformed the native scheme in various simulation setups.

4.4.1 Motivational simulations

This set of simulations reflect the motivations behind the proposed frame-type-differentiated queue management scheme. The simulation parameters can be seen in Table 4.2. The number of lost packets is varied from one to all packets and the effect of several drop mechanisms are analyzed.

Table 4.2 : Simulation parameters for motivational simulations.

Notation	Explanation	Value/s
N_T	Total number of packets (for all videos)	87
N_I	Number of I frames within packet	1
N_P	Number of P frames within packet	3
N_B	Number of B frames within packet	7
N_L	Number of lost packets	Swept from 0 to 87

In the figures, *'Random Packets'* labeled curves represent the cases where there is no discrimination among the packets in terms of loss probability. *'Only B/P/I Packets'* labeled curves represent all the packet losses are form B/P/I packets, respectively. The *'Random Packets'* labeled curves represents the native scheme performance where a channel selector or queue manager does not discriminate packets waiting in its queue. *'Only B/P/I Packets'* labeled curves represents the best and the worst case scenarios where the least and the most important packets are dropped.

Figure 4.8 visualizes the decodable frame rate ratio of several drop mechanisms denoted by the Q metric. Even if the individual perceptual quality contribution varies from packet to packet, for noisy environments like CRNs, the dominating perceptual quality degradation effect would result from the packet loss instead, which makes the Q one of the most important metrics in the system.

As it can be observed from the curves in Figure 4.8, the smallest degradation is seen for the case where all the packet loss is from the B packets. This is stemming from the

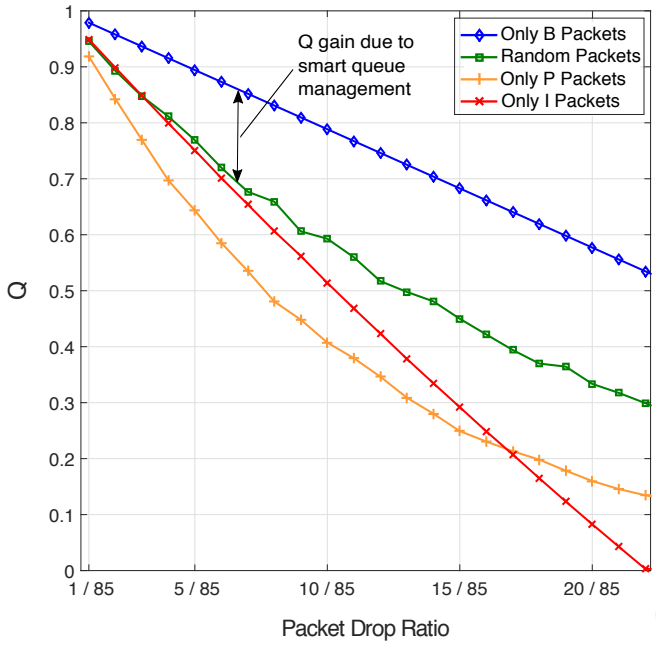


Figure 4.8 : Q of different packet drop mechanisms for all videos.

decoding dependencies of MPEG-2, in which any packet loss results with additional losses due to the dependent frames except for the B packets.

Figure 4.9, Figure 4.10 and Figure 4.11 visualizes the PSNR-Y performance of several drop mechanisms for the three sample videos used. Same trend that is observed from performance metric Q results is also seen for PSNR-Y performance for all videos, matching with the motivations behind the proposed smart queue management.

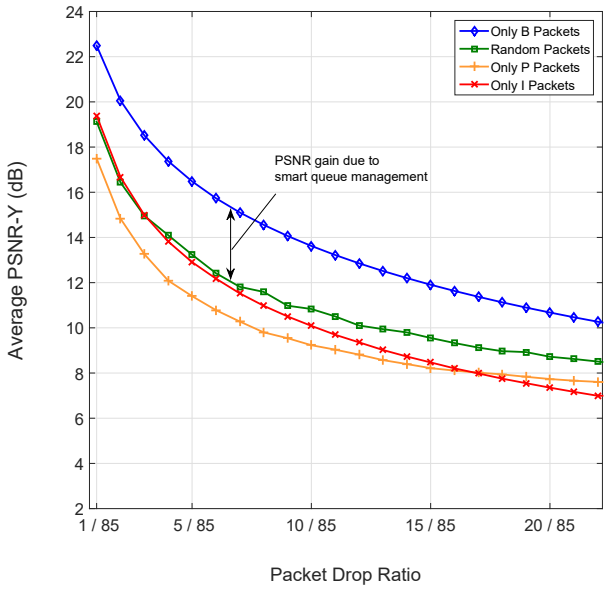


Figure 4.9 : PSNR-Y of different packet drop mechanisms for video: Football.

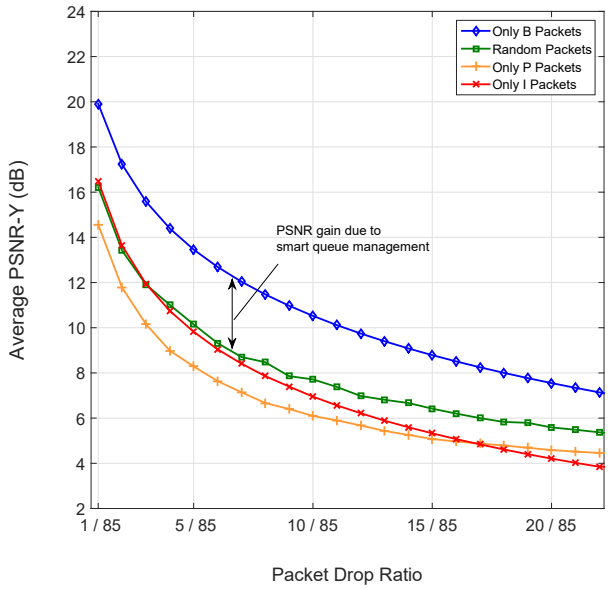


Figure 4.10 : PSNR-Y of different packet drop mechanisms for video: Washington.

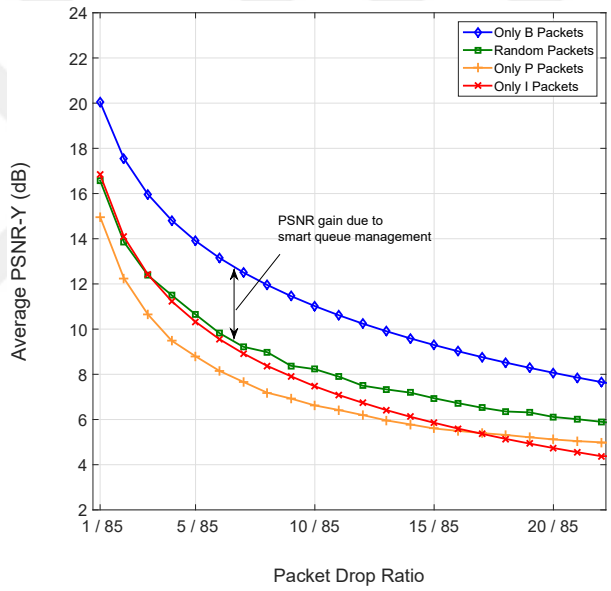


Figure 4.11 : PSNR-Y of different packet drop mechanisms for video: Galleon.

Figure 4.12, Figure 4.13 and Figure 4.14 visualizes the MSSIM-Y performance of several drop mechanisms for the three sample videos used. MSSIM-Y performance also decreases with increased packet loss rate for all videos. *'Only B Packets'* and *'Only IIP Packets'* mechanisms have the best and the worst performances, respectively.

As it can be seen from , Figures 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, and 4.14, all performance metrics highly decrease when all of the packet loss resulted from the loss of I or P packets. The best performance can be obtained when all loss comes from B packets.

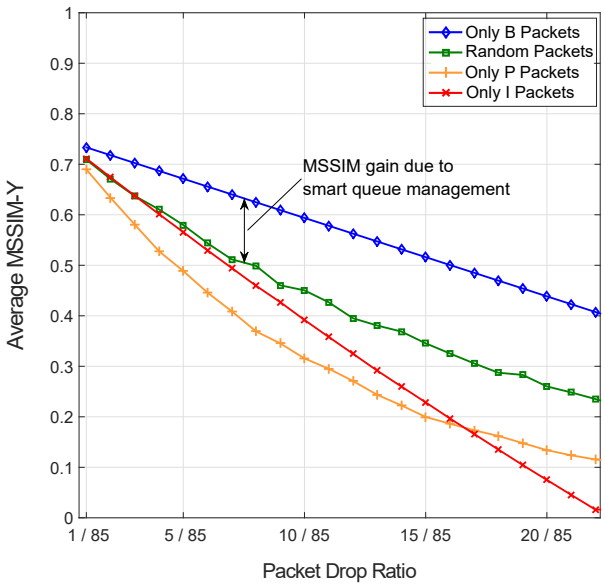


Figure 4.12 : MSSIM-Y of different packet drop mechanisms for video: Football.

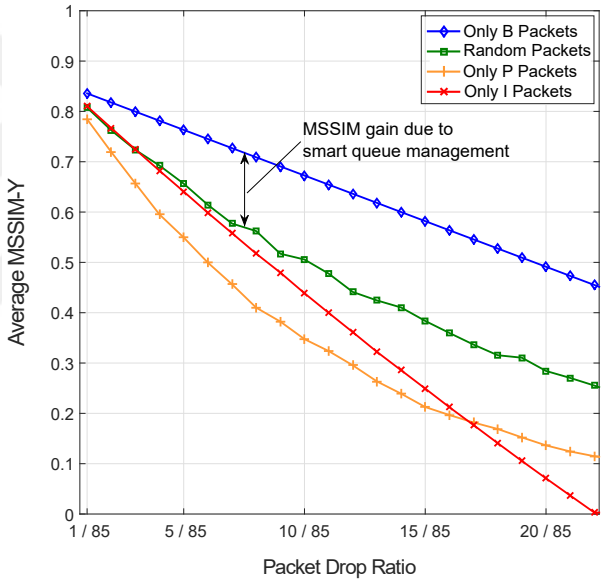


Figure 4.13 : MSSIM-Y of different packet drop mechanisms for video: Washington.

In a real network scenario, it may not be possible to arrange the packets such that all the packet loss will be from the B packets. However, using the proposed queue management, as the I and B packets will precede the B packets in the transmission queue, their probability of packet loss for them due to the timeout is lower than the B packets, leading to a better visual perceptual quality.

4.4.2 Model simulations

In this set of simulations, the same GOP pattern is used and the same test videos as in the motivational simulations. However, instead of setting the packet loss probabilities

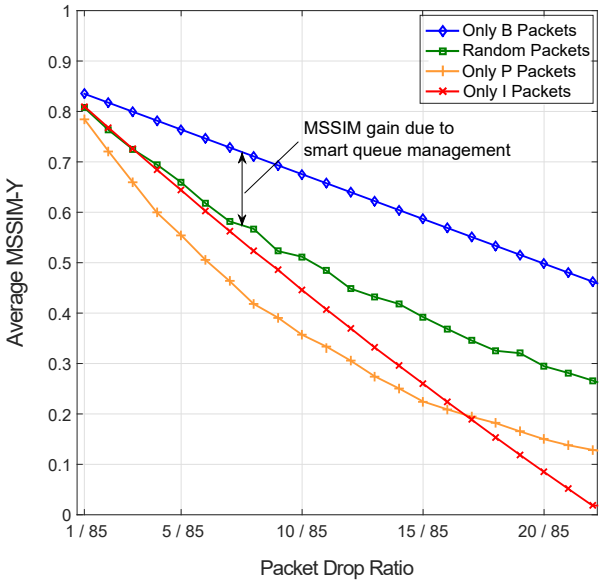


Figure 4.14 : MSSIM-Y of different packet drop mechanisms for video: Galleon.

in a controlled manner, the network model described in Section 4.2 is employed. The network model related parameters used in these simulations are summarized in Table 4.3.

Table 4.3 : Simulation parameters for model simulations.

Notation	**Explanation**	**Value/s**
$\mu_{ON,\ heavy}$	PU on period mean for heavily used channels	6
$\mu_{ON,\ sparse}$	PU on period mean for sparsely used channels	0.66
μ_{OFF}	PU off period mean for all channels	2
M	Number of PU channels in system	4
N_H	Number of channels in heavy use	$\{0,1,2,3,4\}$
t_s	Sampling time	1
τ_{delay}	Tolerable delay for all packets	40
T_{SIM}	Simulation time	$\tau_{delay} * M * 1.1 = 176$

Performance comparisons are done with respect to a *Native Scheme* that randomizes the packets, but does not discriminate the frame types while scheduling the packets in the transmission queue.

Figure 4.15 visualizes decodable frame rate ratio for both the proposed and the native scheduling schemes where its decrease is seen by the increase of heavily used channels. The proposed scheduling provides better performance as it tries to benefit from selective drop mechanism among video packets.

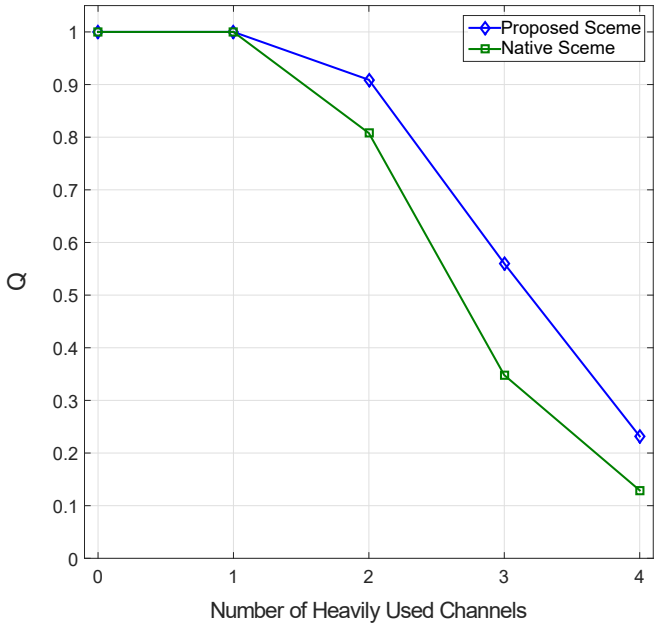


Figure 4.15 : Q of the proposed and the native schemes for all videos.

Figure 4.16, Figure 4.17 and Figure 4.18 visualizes the PSNR-Y performance of the proposed and the native schemes for the three sample videos used. As expected, in both schemes, PSNR-Y performance decreases while the time between the spectrum opportunities increases, leading to increased packet loss. However, it can be observed that the proposed scheme handles the packet loss, that is inevitable by the network structure, in a more intelligent way and performs better than the native scheme.

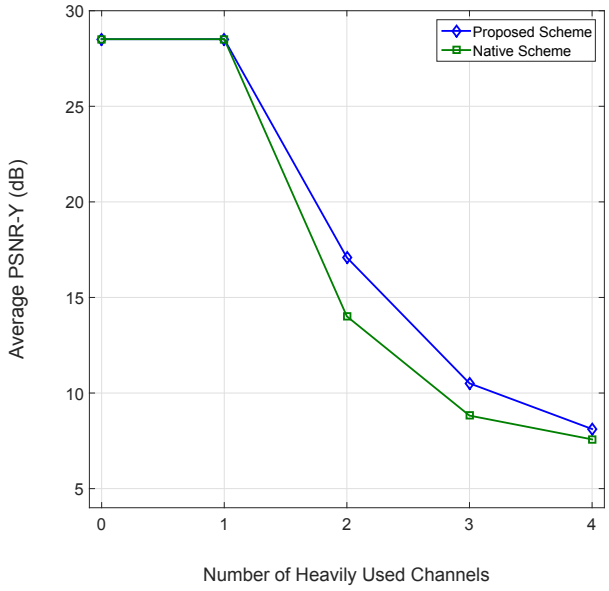


Figure 4.16 : PSNR-Y of the proposed and the native schemes for video: Football.

Figure 4.19, Figure 4.20 and Figure 4.21 visualizes the MSSIM-Y of the proposed and the native schemes for the three sample videos used. The same trend that is observed

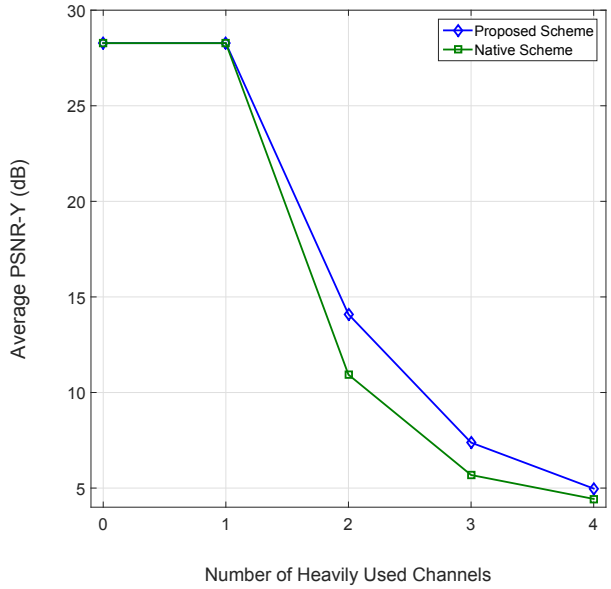


Figure 4.17 : PSNR-Y of the proposed and the native schemes for video: Washington.

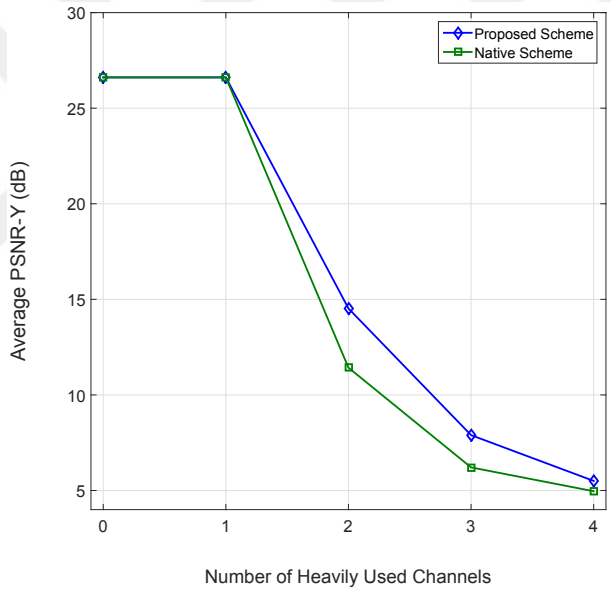


Figure 4.18 : PSNR-Y of the proposed and the native schemes for video: Galleon.

from Q and PSNR-Y results is also seen for MSSIM-Y performance for all videos, as these performance metrics are highly correlated. The proposed scheme provides better MSSIM-Y performance over the native scheme for all channel ratio set-ups and for all sample videos.

As the number of heavily used channels increase, the probability of packet loss increases. That comes from the fact that for a heavily used channel, the time between spectrum opportunities increases. The probability for a packet to reach its timeout thus increases and this leads to increased packet loss probability. This general trend

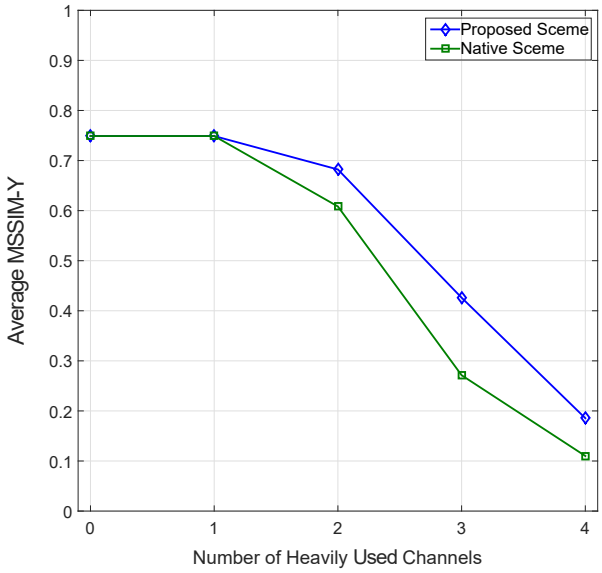


Figure 4.19 : MSSIM-Y of the proposed and the native schemes for video: Football.

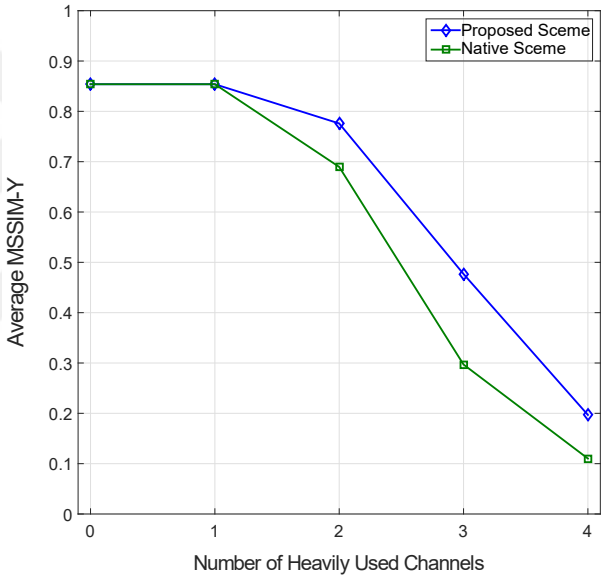


Figure 4.20 : MSSIM-Y of the proposed and the native schemes for video: Washington.

of decrease in the perceptual visual quality metrics as the number of heavily used channels increase is observed for all test videos.

As can be seen from Figures 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, and 4.21, when compared with the native scheme, which places all packets in transmission queue randomly but without any precedence, the proposed queue management scheme performs better in all of the defined performance metrics as it tries to prevent frame dependent additional packet losses.

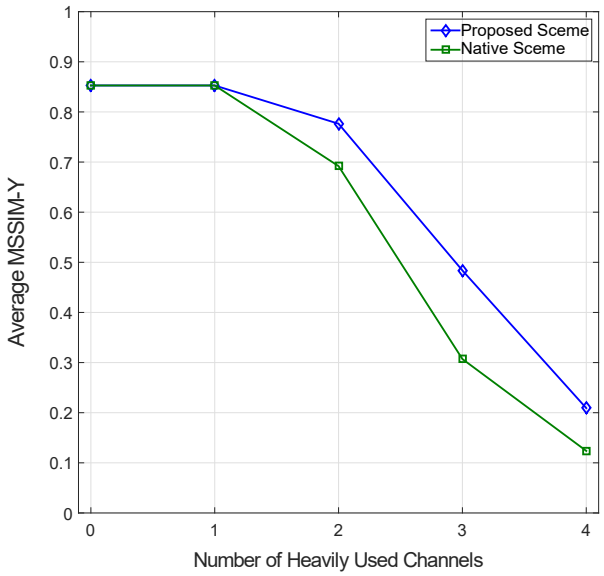


Figure 4.21 : MSSIM-Y of the proposed and the native schemes for video: Galleon.

When the packet loss probability increases beyond a certain point, all packet losses may not be resulting from the loss of least valuable packets (i.e. B packets) and more valuable packets (i.e. I and P packets) can still be lost in the proposed scheme as well. Even so, the number of dependent losses would be smaller than the native scheme.

Since no error concealment method is applied, the packet losses decrease the PSNR-Y and the MSSIM-Y performance drastically. However, it is worth mentioning that the proposed queue management scheme can be assisted in conjunction with any error concealment method to further increase the perceptual visual quality at the receiver side.

5. CONCLUSION AND FUTURE WORK

In this thesis, new approaches for QoS provisioning over CRNs are proposed and evaluated. In this regard, the thesis studies first include the QoS provisioning problem in a broader range, considering heterogeneous traffic types of SUs. In the second part, as a focused case study, MPEG-2 based encoded video transmission problem is investigated and a frame-type-differentiated queuing mechanism is proposed.

First part is detailed in Chapter 3 where a new channel selection and a scheduling method are presented. The proposed channel selection method is a fast, distributed and a PU temporal activity estimation aided spectrum assignment scheme for the SUs with traffic demands at different QoS levels. Temporal PU activity level is estimated by the distributed SUs that only use their local sensing histories via projecting the moving average value of their individual sensing histories into three temporal activity classes. The heuristic packet selection method is devised by leveraging low prioritized packets over high prioritized packets on channels in heavy use in terms of temporal PU activity and used the opposite manner for the channels in sparse use. Motivational heuristics are supported by the proof of concept simulations for a single-channel and a single-user CRN environment. Then, the model and the proposed schemes are expanded into a multi-channel and multi-user CRN setup. Aiming to further increase the overall network utility, supporting scheduling mechanism among contenting SUs is also devised and presented. The proposed schemes are modeled along with their network models in MATLAB®. The performance of the proposed schemes are evaluated with respect to a native scheme that utilities every spectrum opportunity for the high prioritized traffic and the simulations validated the effectiveness of the proposed channel assignment scheme in terms of a *Figure of Merit* metric, reflecting the weighted sum of the throughput ratio values for packets of different QoS levels.

As the second part of the thesis, MPEG-2 based encoded video transmission problem is investigated in Chapter 4 where a distributed queue management scheme is proposed and evaluated. The proposed queue management method changes the transmit order

of the frames in favor of the more valuable ones (i.e. the ones needed by others for them to be decoded) and basically decreases the packet loss probability by sending the reference frames first, in order to prevent indirect frame loss due to the decoding dependencies. The performance of the proposed scheme is investigated with the developed MATLAB® model that is supported by FFmpeg tool for encoding operations. The results validate that the proposed scheme outperformed the native scheme, that does not discriminate any internal frame type information among the video packets, in various simulation setups in terms of several video quality metrics, namely: Peak Signal to Noise Ratio (*PSNR*), Mean Structural SIMilarity metric (*MSSIM*), and decodable frame ratio (Q).

The importance of this thesis comes from the lightweight solutions presented for the efficient spectrum management and quality of service provisioning for multimedia traffic transmission. Thesis studies cover several CRN models and novel channel assignment and scheduling strategies.

As future work, counter-measures for probable drawbacks of the proposed schemes are planned. One example is an implementation and a performance evaluation of the channel borrowing functionality, that can be applied using local neighboring control messaging prior to scheduling for more efficient use of spectrum opportunities in the environments where some of the SUs have very low traffic loads. The additional complexity of this neighboring messaging trade-off with the gain in spectrum hole utility then has to be investigated. For the second part of the thesis, changing the encoding type from MPEG-2 to another standard like SVC is planned as a future work along with the required adoption studies.

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APPENDICES

APPENDIX A: SU Service Time Distribution Approximation Details
APPENDIX B: MATLAB Simulink® Model for Multi-Channel, Multi-User Cognitive Radio Environment
APPENDIX C: Detailed Definition of the Peak Signal to Noise Ratio and Q Perceptual Video Quality Metrics used in Chapter 4

APPENDIX A

As the SU transmission are interrupted by the privileged PU traffic, all performance metrics defined for the SU traffic are highly affected by the PU traffic pattern. The most important statistics for a high prioritized SU packet is the probability for it to be timed-out due to increased waiting time.

The probability for a random packet to be timed-out is highly dependent on the probability of the packets ahead being timed-out or not. Therefore, as a starting point, the service time distribution for an SU is analyzed. Under the assumption of perfect alignment between the SU sampling instances and PU activity rising edges, and considering that, by design, the sampling rate t_s is much smaller than the PU active period T_{ON}, an approximation is presented for SU service time distribution. This approximation is validated with the performed analytical simulations.

In the network models used in this thesis, the PU Poisson traffic is sampled by an SU with a fixed sampling rate (See: Figure 3.1). As demonstrated in Figure 3.1, SU service time equals to sampling period when the PU is in inactive duration. When the PU is in active duration, the service time differs along with the PU active period length.

Probability of service time being equal to $n * ts$ is then derived as follows for three cases:

Case 1 : $n < 1$**:** Resulting from the sampled operation mode of SUs, by design, the service time of an SU cannot be smaller than one sampling period, resulting with zero possibility.

Case 2 : $n = 1$**:** This case happens when the PU is in inactive period and the SU can serve a new packet at each sample, making inter-service time of SU packets exactly one t_s.

PUs in the network model have Poisson traffic patterns with means of μ_{ON} and μ_{OFF} for their on and off periods, respectively. Therefore, the expected duration of an inactive period is μ_{OFF}.

In a single PU active period followed by an inactive period (T_{off}), the service time of the SU equals to t_s for $\frac{T_{off}}{t_s}$ times and equals to a longer duration (that will be derived in next case) for 1 time (in PU's active period). As the expected duration of an inactive period is μ_{OFF}, probability for service time to be equal to a single sampling period becomes:

$$\frac{\frac{\mu_{off}}{t_s}}{\frac{\mu_{off}}{t_s}+1} \tag{A.1}$$

Case 3 : $n > 1$**:** This situation is observed with probability $\frac{1}{\frac{\mu_{off}}{t_s}+1}$ as explained in Case 2. Probability for the service time to be $n * t_s$ given that the PU is in active period can be derived using the exponential distribution properties of the PU active period.

Figure A.1 represents a numerical example where the PU active period has to be between 2 and 3 for an SU service time to be equal to 4. The arrows in the figure represents SU service instances. Case 2 can be seen where service time equals to 1 in PU inactive periods. For Case 3, limits on PU active period is demonstrated. By

the perfect alignment assumption, same last service instance can be followed by a PU active period that is bounded between $(2,3] * t_s$ giving $4 * t_s$ service time.

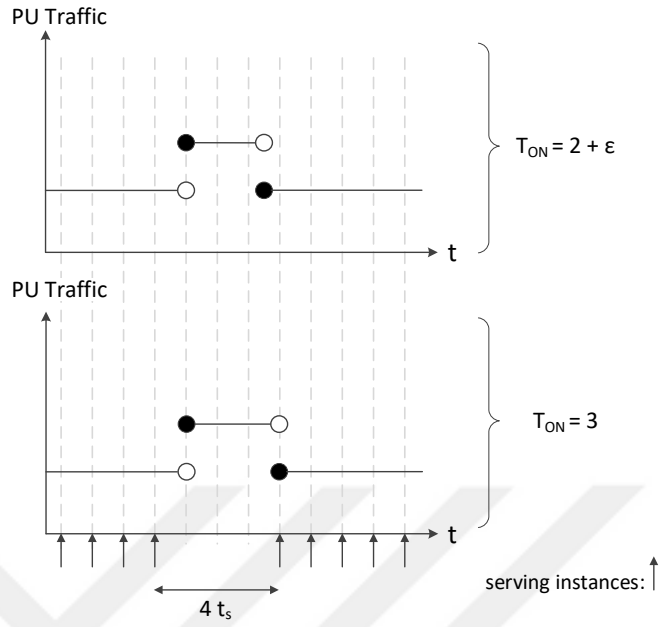

Figure A.1 : T_{ON} limits for SU service time equals $4 * t_s$.

Therefore, for the SU service time to be equal to $n * t_s$, the PU active period has to hold below condition:

$$n-2 < T_{ON} \leq n-1 \tag{A.2}$$

By using the cumulative distribution function of the exponential distribution of PU active period, probability for T_{ON} to be in this interval can be written as:

$$\begin{aligned} \Pr\{serviceTime = n * t_s\} &= F((n-1) * t_s) - F((n-2) * t_s) \\ &= (1 - e^{-\lambda(n-1)t_s}) - (1 - e^{-\lambda(n-2)t_s}) \\ &= e^{-\lambda(n-2)t_s}(1 - e^{-\lambda t_s}) \end{aligned} \tag{A.3}$$

Combining the derivations in all cases, the SU service time distribution approximation becomes:

$$\Pr\{serviceTime = n * ts\} = \begin{cases} 0 & n < 1 \\ \frac{\frac{\mu_{off}}{t_s}}{\frac{\mu_{off}}{t_s}+1} & n = 1 \\ \frac{1}{\frac{\mu_{on}}{t_s}+1} e^{-\lambda t_s(n-2)}(1 - e^{-\lambda t_s}) & n > 0 \end{cases} \tag{A.4}$$

$given : \lambda \triangleq \frac{1}{\mu_{on}}$

The infinite sum of this approximated probability distribution is verified to be equal to 1 using Wolfram Mathematica® tool. The probability distribution of the SU service time simulations can be seen from Figures A.2 and A.3. As a result of perfect alignment assumption, the simulation and the formulated analytical results do not match perfectly.

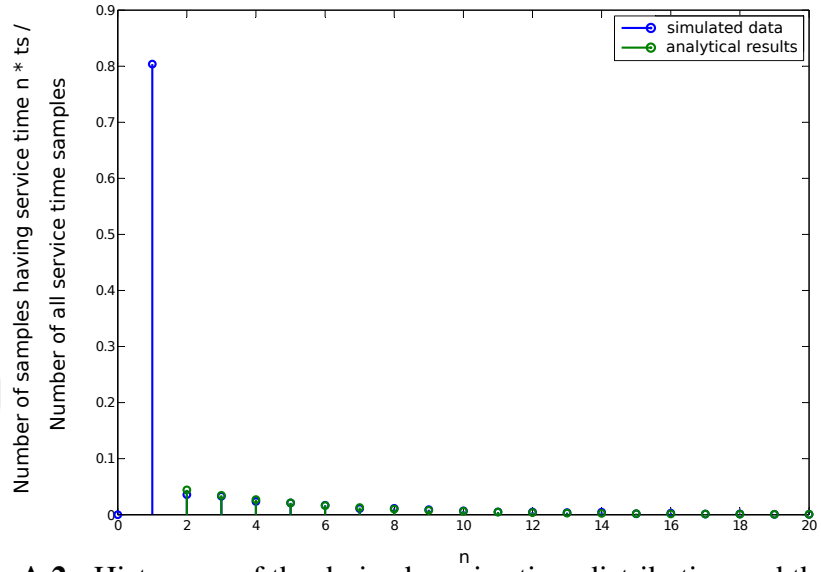

Figure A.2 : Histogram of the derived service time distribution and the simulation results (PU traffic for 10000 samples and $t_s = 1$).

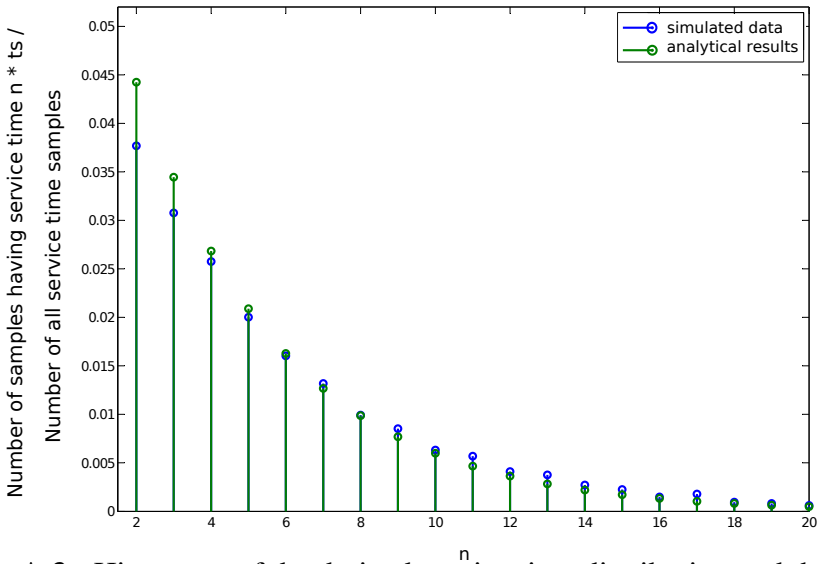

Figure A.3 : Histogram of the derived service time distribution and the simulation results (Focused for $n > 1$ case).

When this service time distribution is convoluted, the number of the terms in the resulting expression increases at each step. Therefore, the average number of customers in the queue employing this service time can not be derived in closed form. As a result, the packet loss due to a time-out probability of an SU packet also could not be derived in closed form.

APPENDIX B

The top-level view of the designed MATLAB Simulink® model,can be seen in Figure B.1 where the number of SUs is 2 and the number of PU channels is 10.

The SU traffic generator module utilizes queuing related components from MATLAB Simulink® SimEvents Library, as demonstrated in Figure B.2.

The SU model includes a PU traffic classifier, a packet selection algorithm module and a queue manager for handling queue management operations. These modules can be seen in Figure B.3.

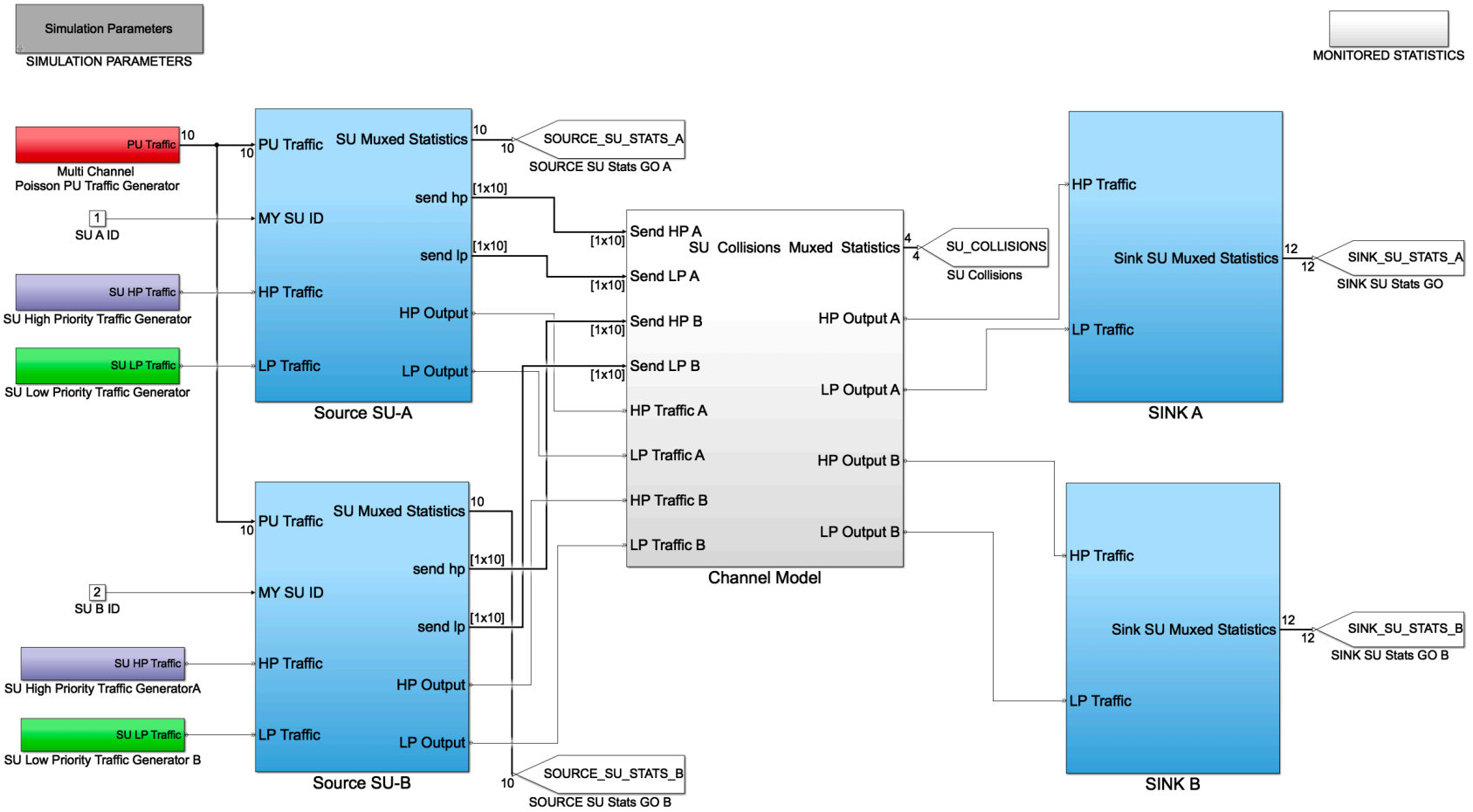

Figure B.1 : MATLAB Simulink® model, top-level view.

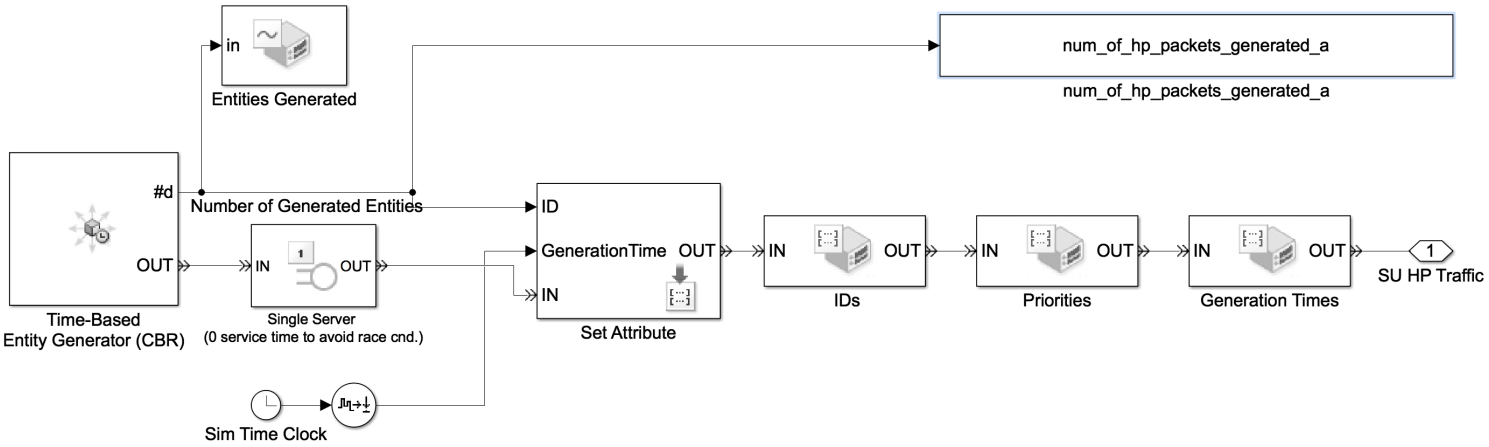

Figure B.2 : MATLAB Simulink® model, SU traffic generator system view.

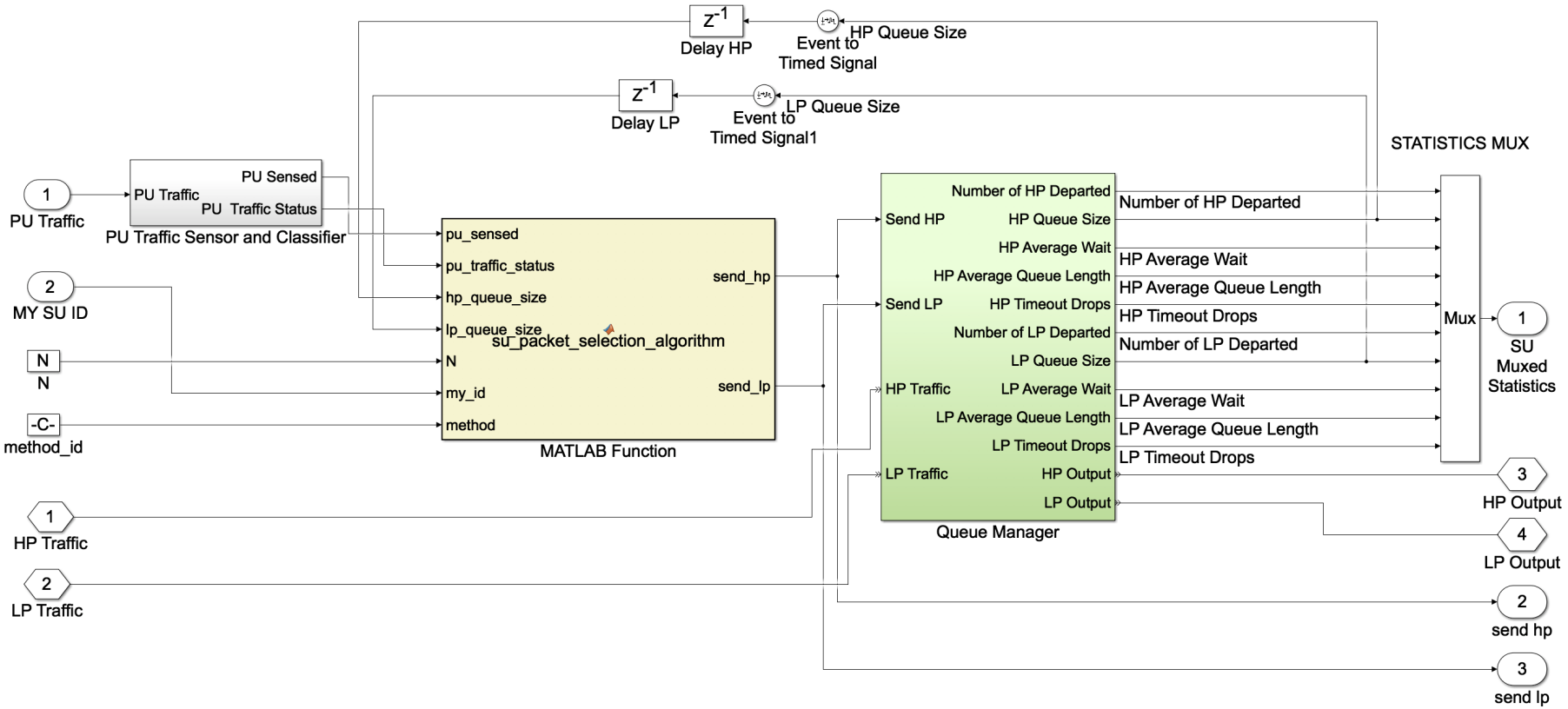

Figure B.3 : MATLAB Simulink® model, SU module view.

The PU classification module utilizes the moving averaging window projection into three activity classes as explained in Section 3.1.2 for which related MATLAB Simulink® modules are presented in Figure B.4.

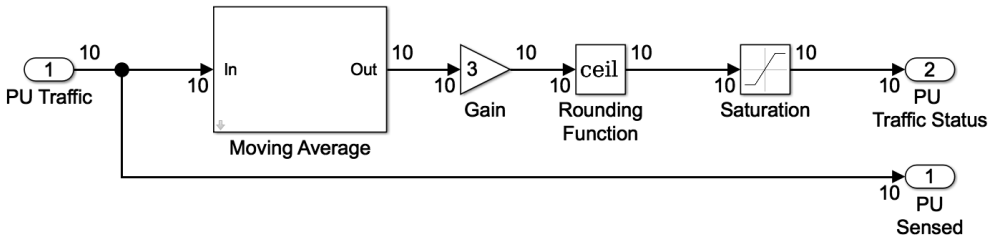

Figure B.4 : MATLAB Simulink® model, PU classification system view.

When multi-user model is employed, the probable collisions among contending SUs are modeled within a main channel module for which the inner modules are visualized in Figure B.5.

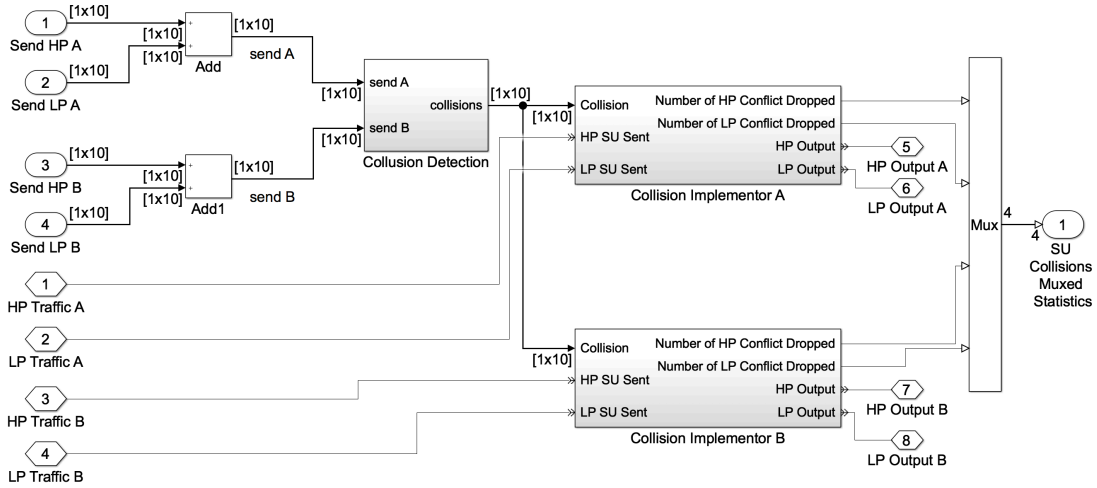

Figure B.5 : MATLAB Simulink® model, channel module view.

APPENDIX C

Peak Signal to Noise Ratio (PSNR) is one of the most commonly used perceptual video quality metric in reference works. In the thesis studies, the PSNR decrease between an original video frame and a decoded received video frame is dominated by packet loss instead of an encoder loss. An undecodable frame in receiver side results in a black image in terms of Y component that highly increases mean squared error (MSE) between the received/decoded and the original frames.

PSNR calculation uses MSE that represents the mean of sum of squared error of each pixel between the received and the original frames. Figure C.1 includes 4x4 original and received sample frames with random pixel values. The squared error frame given in the figure represents how the squared error is calculated. Figure C.2 includes the MSE calculation example for sample frames in Figure C.1 as a sum of squared errors divided by the number of pixels.

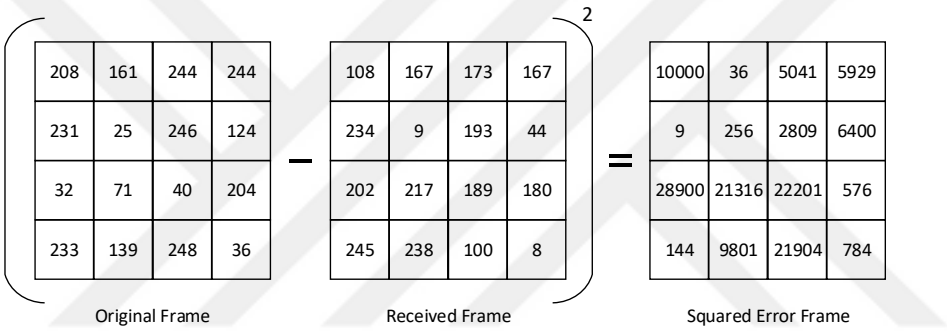

Figure C.1 : Random frame pixels and sample squared error frame.

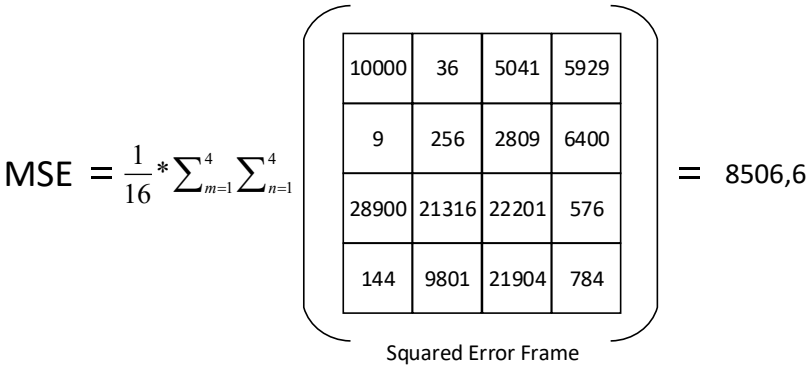

Figure C.2 : Sample mean squared error calculation.

The PSNR represents the ratio of the maximum signal power and the MSE. The maximum signal power is the square of the maximum pixel value denoted by R. Thus, the PSNR metric in decibels is defined as follows:

$$PSNR = 10\ log\frac{R^2}{MSE} \tag{C.1}$$

In the thesis studies,the simulation results include a measurement of the average PSNR performance of the sample videos. As the PSNR is a logarithmic quantity, the average PSNR of a video with N frames is defined as in Equation C.2.

$$PSNR_{AVG} = 10\ log\frac{R^2}{MSE_{AVG}},\ where\ MSE_{AVG} = \frac{1}{N}\sum^{N} MSE_i \tag{C.2}$$

The performance metric Q is the decodable frame ratio that is defined as the number of successfully decoded frames over total number of frames. The number of undecodable frames is higher than the number of dropped frames except for a special condition when all of the dropped frames are B frames, in which case two numbers become equal. The reason behind is that whenever a reference frame (I or P) is subjected to a packet loss, its encoding related dependent frames cannot be decoded. All probabilities for reference frame losses can be seen in Figure C.3. Within a single GOP, the loss of an I frame causes the loss of 16 other dependent frames. Similarly the loss of a P frame causes the loss of an additional 4, 7, 10 or 13 frames, depending on the position of the P frame inside GOP.

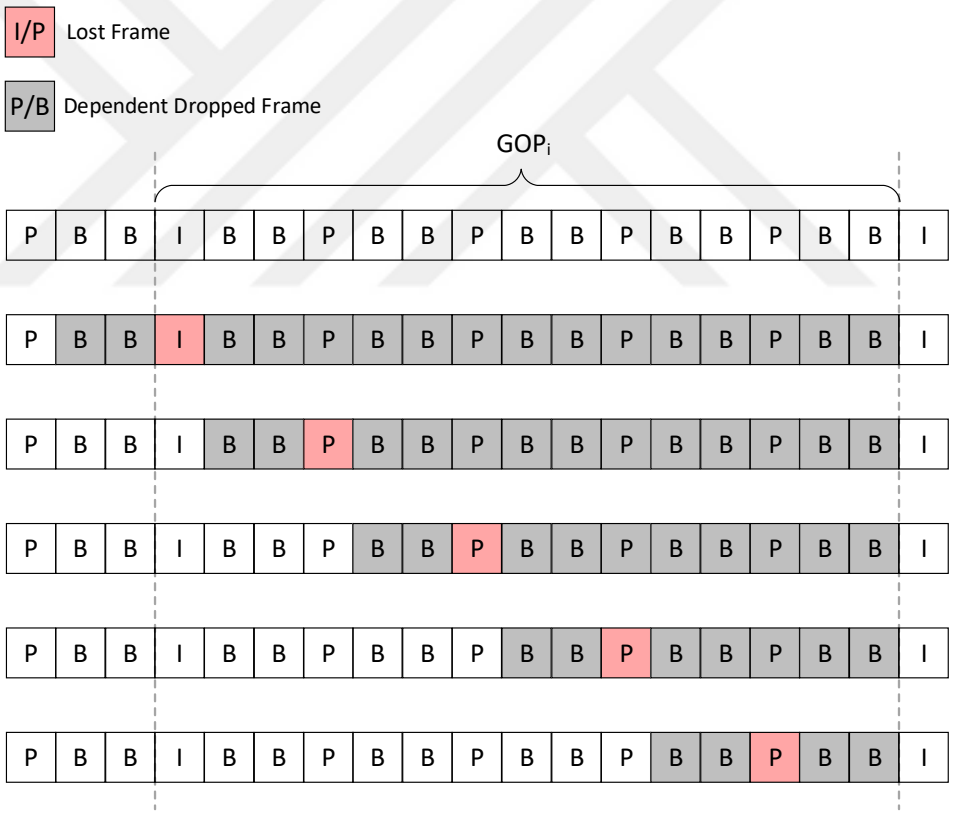

Figure C.3 : Lost frames and related dependent drops within GOP.

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