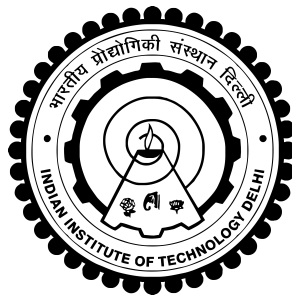


**PERFORMANCE OF AN UNDERLAY  
COOPERATIVE COGNITIVE NETWORK WITH A  
BUFFER-AIDED-RELAY**

**BHUPENDRA KUMAR**



**BHARTI SCHOOL OF TELECOMMUNICATION  
TECHNOLOGY AND MANAGEMENT  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
MARCH 2019**

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*by*

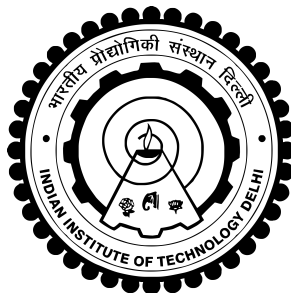
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*submitted*

*in fulfillment of the requirements of the degree of Doctor of Philosophy*

*to the*



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**MARCH 2019**

# CERTIFICATE

This is to certify that the thesis titled **Performance of an Underlay Cooperative Cognitive Networks with a Buffer-Aided Relay**, submitted by **Mr. Bhupendra Kumar**, to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

**Dr. Shankar Prakriya**  
Professor  
Department of Electrical Engineering  
Indian Institute of Technology, Delhi

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Bhupendra Kumar

## ABSTRACT

The ever-increasing demand for wireless services requiring high data rates with low latency, and increasing need for seamless connectivity with good user quality of service and experience, pose great technological challenges that need to be overcome. A lot of research effort has therefore focussed on these challenges. To improve spectrum utilization efficiencies, use of underlay cognitive radio techniques is being explored. Relays have been incorporated into new standards to increase range and reliability of links. When the relays are of half-duplex type, a rate penalty is incurred. In cooperative networks, harnessing diversity is known to be key to attaining good performance. Combining the direct and the relayed links, or using relay selection are options. In recent years, it has been shown in the cooperative context that adaptive link selection in a two-hop network can yield additional diversity gain. However, to make this possible, the relay has to be equipped with a data buffer. A range of issues related to rate, symbol-error probability, and delay performance arise.

Since the sources in underlay cognitive radio networks are power-limited, reliable communication is only possible over relatively short distances. Use of relays is thus well motivated. Further, the interference constraints imposed by the primary network in underlay cognitive radio makes the power available at the secondary nodes a random quantity. Coupled with fading nature of the channels, this ensures that the signal to noise ratios in each of the two-hops show high variability. Use of adaptive link selection with buffer-aided relays is therefore very well motivated in underlay cognitive radio networks. The thesis examines the performance of an underlay cognitive radio network with a decode-and-forward based dual-hop half-duplex buffer-aided relay. The thesis analyzes the ergodic rate performance of such networks with continuous adaptive-rate transmission. It is clearly demonstrated that adaptive link selection is important in underlay scenarios. The thesis also analyzes the loss incurred in rate when delay-constraints are imposed. In addition, the symbol error rate performance is analyzed for fixed-rate transmission. The analysis highlights the importance of link selection in de-

lay tolerant systems. Moreover, the thesis investigates the analytical trade-off between delay, throughput and symbol error rate for finite buffer size and starving buffer cases.

Due to variability of signal to noise ratios (SNRs), use of a discrete rate-set is well motivated. This thesis further analyzes the throughput performance when the secondary source and relay use multiple rate sets instead of adapting their rate, or use a single rate. The source to destination direct link is also exploited. In order to maximize the throughput, the thesis first develops the joint rate and link-selection rule, and then analyzes the buffer-stability condition. The thesis then provides expressions for link and system throughput when operating at the optimum stability point. These results have been applied to two schemes. While the first merely performs adaptive link selection among the three links, the second scheme combines the direct and relayed signals. We show that link selection of buffered and the direct path enables us to harness most of the throughput potential of underlay cognitive radio networks, and combining the direct and relayed signals offers little additional throughput gain. The thesis then investigates the effect of finite-sized buffer on throughput and delay.

## सार

कम विलंबता के साथ उच्च डेटा दरों की आवश्यकता वाली वायरलेस सेवाओं के लिए लगातार बढ़ती मांग, और सेवा और अनुभव की अच्छी उपयोगकर्ता गुणवत्ता के साथ सहज कनेक्टिविटी की बढ़ती आवश्यकता, महान तकनीकी चुनौतियों का सामना करना पड़ता है। इसलिए कई शोध प्रयासों ने इन चुनौतियों पर ध्यान केंद्रित किया है। स्पेक्ट्रम उपयोग क्षमता में सुधार करने के लिए, अंडरले संज्ञानात्मक रेडियो तकनीकों के उपयोग का पता लगाया जा रहा है। लिंक की सीमा और विश्वसनीयता बढ़ाने के लिए रिले को नए मानकों में शामिल किया गया है। जब रिले आधे-द्वैध प्रकार के होते हैं, तो दर में कमी होती है। सहकारी नेटवर्क में, विविधता का दोहन अच्छे प्रदर्शन को प्राप्त करने के लिए महत्वपूर्ण माना जाता है। प्रत्यक्ष और रिलेटेड लिंक को जोड़ना, या रिले सिलेक्शन का उपयोग करना अच्छा विकल्प हैं। हाल के वर्षों में, यह सहकारी संदर्भ में दिखाया गया है कि दो-हॉप नेटवर्क में अनुकूली लिंक का चयन अतिरिक्त विविधता हासिल कर सकता है। हालांकि, इसे संभव बनाने के लिए, रिले को डेटा बफर से लैस करना होगा। दर, प्रतीक-त्रुटि संभावना और देरी प्रदर्शन से संबंधित मुद्दों की एक श्रृंखला उत्पन्न होती है।

चूँकि अंडरले संज्ञानात्मक रेडियो नेटवर्क के स्रोत शक्ति-सीमित हैं, इसलिए विश्वसनीय संचार अपेक्षाकृत कम दूरी पर ही संभव है। रिले का उपयोग इस प्रकार अच्छी तरह से प्रेरित है। इसके अलावा, प्राथमिक संज्ञानात्मक रेडियो में प्राथमिक नेटवर्क द्वारा लगाए गए हस्तक्षेप बाधाओं को माध्यमिक नोड्स में एक अनियमित मात्रा में उपलब्ध शक्ति बनाता है। चैनलों की लुप्त होती प्रकृति यह सुनिश्चित करती है कि प्रत्येक दो-हॉप्स में एस.एन.आर. उच्च परिवर्तनशीलता दिखाते हैं। बफर एडेड रिले के साथ अनुकूली लिंक चयन का उपयोग इसलिए बहुत अच्छी तरह से अंडरले संज्ञानात्मक रेडियो नेटवर्क में प्रेरित है। शोध प्रबंध डिकोड-एंड-फॉरवर्ड आधारित दोहरे-हॉप हाफ-डुप्लेक्स बफर-एडेड रिले के साथ एक अंडरले संज्ञानात्मक रेडियो नेटवर्क के प्रदर्शन की जांच करता है। शोध प्रबंध निरंतर अनुकूली-दर संचरण के साथ ऐसे नेटवर्क के एर्गोडिक दर प्रदर्शन का विश्लेषण करता है। यह स्पष्ट रूप से दर्शाया गया है कि आधारभूत परिदृश्यों में अनुकूली लिंक का चयन महत्वपूर्ण है। शोध प्रबंध दर में कमी का विश्लेषण भी करती है जब देरी-बाधाएं लगाई जाती हैं। इसके अलावा, फिक्स्ड-रेट ट्रांसमिशन के लिए प्रतीक त्रुटि दर प्रदर्शन का विश्लेषण किया जाता है। विश्लेषण देरी सहिष्णु प्रणालियों में लिंक चयन के महत्व पर प्रकाश डालता है। इसके अलावा, शोध प्रबंध बफर, बफर आकार और भूखे बफर मामलों के लिए देरी, थ्रूपुट और प्रतीक त्रुटि दर के बीच विश्लेषणात्मक समझौताकारी समन्वयन की जांच करता है।

एस.एन.आर को संकेत की परिवर्तनशीलता के कारण, डिस्क्रीट दर-सेट का उपयोग अच्छी तरह से प्रेरित है। यह शोध प्रबंध आगे थ्रूपुट प्रदर्शन का विश्लेषण करती है जब माध्यमिक स्रोत और रिले अपनी दर को बढ़ाने के बजाय कई दर सेट का उपयोग करते हैं, या एकल दर का उपयोग करते हैं। डायरेक्ट लिंक को डेस्टिनेशन करने के स्रोत का भी उपयोग होता है। थ्रूपुट को अधिकतम करने के लिए, शोध प्रबंध पहले संयुक्त दर और लिंक-चयन नियम विकसित करता है, और फिर बफर-स्थिरता की स्थिति का विश्लेषण करता है। शोध प्रबंध तब इष्टतम

स्थिरता बिंदु पर काम करते समय लिंक और सिस्टम थ्रूपुट के लिए अभिव्यक्ति प्रदान करता है। ये परिणाम दो योजनाओं पर लागू किए गए हैं। जबकि पहला केवल तीन लिंक के बीच अनुकूली लिंक का चयन करता है, दूसरी योजना प्रत्यक्ष और रिले सिग्नल को जोड़ती है। हम दिखाते हैं कि बफर किए गए लिंक का चयन और सीधा रास्ता हमें अंडरले संज्ञानात्मक रेडियो नेटवर्क के अधिकांश थ्रूपुट क्षमता का दोहन करने में सक्षम बनाता है, और प्रत्यक्ष और रिलेटेड सिग्नल के संयोजन से थोड़ा अतिरिक्त थ्रूपुट लाभ मिलता है। शोध प्रबंध तब थ्रूपुट और देरी पर परिमित आकार के बफर के प्रभाव की जांच करती है।

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## ACRONYMS

<b>AM</b>	Amplitude Modulation
<b>AF</b>	Amplify and Forward
<b>AWGN</b>	Additive White Gaussian Noise
<b>bpcu</b>	Bits Per Channel Use
<b>CABR</b>	Channel Aware Buffered Relay
<b>CBR</b>	Conventional Buffered Relay
<b>CCDF</b>	Complementary Cumulative Distribution Function
<b>CNBR</b>	Conventional Non-Buffered Relay
<b>CR</b>	Cognitive Radio
<b>CRN</b>	Cognitive Radio Network
<b>CSI</b>	Channel State Information
<b>CT</b>	Constant Throughput
<b>DF</b>	Decode-and-Forward
<b>FD</b>	Full-Duplex
<b>FDD</b>	Frequency Division Duplex
<b>FM</b>	Frequency Modulation
<b>HD</b>	Half-Duplex
<b>IoT</b>	Internet of Things
<b>IIT</b>	Indian Institute of Technology
<b>ITL</b>	Interference Temperature Limit
<b>LSP</b>	Link Selection Probability
<b>LTE</b>	Long Term Evolution
<b>MC</b>	Markov Chain
<b>MDMT</b>	Maximum Delay Minimum Throughput
<b>MIMO</b>	Multiple Input Multiple Output
<b>NOMA</b>	Non Orthogonal Multiple Access
<b>OSTBC</b>	Orthogonal Space Time Block Codes
<b>PAN</b>	Personal Area Network

<b>PDF</b>	Probability Density Function
<b>PIP</b>	Peak Interference Power
<b>PTP</b>	Peak Transmit Power
<b>QAM</b>	Quadrature Amplitude Modulation
<b>QoS</b>	Quality of Service
<b>RC</b>	Rate Constellation
<b>SER</b>	Symbol Error Rate
<b>SNR</b>	Signal-to-noise-ratio
<b>STM</b>	State Transition Matrix
<b>STP</b>	State Transition Probability
<b>TDD</b>	Time Division Duplex
<b>TV</b>	Television
<b>TVWS</b>	TV White Space
<b>WLAN</b>	Wireless Local Area Network

## NOTATION

$ \cdot $	Absolute value
$(\cdot)!!$	Double factorial
$\Gamma(\cdot)$	Gamma function defined on the complex plane except for 0 and, negative integers, where $\Gamma(z) = \int_0^{\infty} t^{z-1} e^{-t} dt$
$\kappa$	Path loss exponent
$\mathcal{CN}(0, \Omega)$	Zero mean complex Gaussian distribution with zero mean and variance $\Omega$
$C$	Instantaneous channel capacity
$\mathcal{C}$	Ergodic capacity
$Di_2(\cdot)$	Dilogarithm function in terms of Spence's integral, where $Di_2[x] = - \int_1^x \frac{\ln(t)}{t-1} dt$
$\operatorname{erfc}(\cdot)$	
$\exp(\cdot)$	Exponential function
$E_p(\cdot)$	Generalized exponential integral for real non-zero values of order $p$ , where $E_p(x) = \int_1^{\infty} t^{-p} e^{-xt} dt \quad (p = 0, 1, 2, \dots)$
$\mathbb{E}_X$	Expectation over random variables $X$
$\mathbb{E}_{X,Y}(\cdot, \cdot)$	Expectation over random variables $X$ and $Y$
$f_X(\cdot)$	Probability density function of random variable $X$
$f_{X,Y}(\cdot, \cdot)$	Probability distribution function (PDF) w.r.t. $X$ and $Y$
$F_X^c(\cdot)$	Complementary cumulative distribution function (CCDF) w.r.t. $X$
$F_{X,Y}^c(\cdot, \cdot)$	CCDF w.r.t. $X$ and $Y$
$I_p$	Interference temperature limit
$L$	Buffer length
$N_0$	Noise variance
$P_{max}$	Secondary peak power
$\Pr\{\cdot\}$	Probability
$q_{l,m}$	State transition probability from state $l$ to $m$
$\mathcal{P}$	Outage probability
$R$	Transmission rate
$\mathcal{S}$	Symbol error rate (SER)
$\overline{T}$	Throughput
$\overline{T}$	Average Delay
$u(\cdot)$	unit step function
$v$	Link selection variable