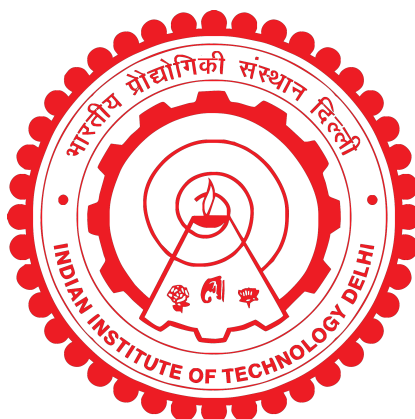


PATH SELECTION IN MULTI-HOP COGNITIVE RADIO NETWORKS

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DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2018

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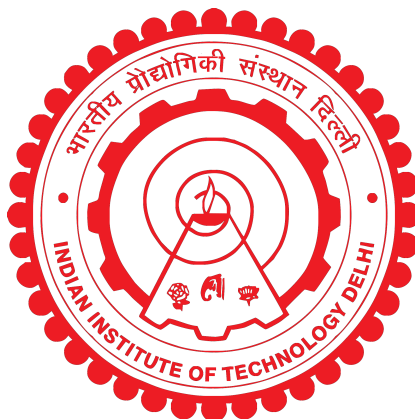
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Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2018

Certificate

This is to certify that the thesis entitled “**Path Selection in Multi-Hop Cognitive Radio Networks**” being submitted by **Mr. Hari Krishna Boddapati** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Acknowledgements

First and foremost, my deepest gratitude to my supervisors Prof. Manav Bhatnagar and Prof. Shankar Prakriya for their expert guidance, constant support, and immense encouragement throughout my Ph.D. program. Their invaluable suggestions and insightful discussions made me enjoy my research. Also their enormous enthusiasm, honest dedication, and quest for knowledge is truly inspirational. My sincere appreciation also extends to Prof. S.D. Joshi, Dr. Brejesh Lall, and Dr. Monika Aggarwal for their beneficial feedback and suggestions during my work.

I acknowledge my friends, Lakshmi Vara Prasad Dhulipalla, Partha Pratim Paul, Manohar Kumar Parvatini, Saptarshi Ghosh, and Ankit Garg for their moral and financial support during my Ph.D. program. Without their help I would have faced many difficulties while doing my Ph.D. program.

I thank my parents Mr. Yallaiah Boddapati and Mrs. Sulochana Boddapati, and my sister Mrs. Hari Thulasi Rani, for encouraging me to do Ph.D, keeping trust in me, and having patience. Most importantly, I am indebted to all the teachers and supervisors in my academic career who helped me to become what I am today, and whatever I have achieved so far, I owe it to all of them.

Hari Krishna Boddapati

Abstract

There is a restriction on the transmit power of secondary users (SUs) in underlay cognitive radio networks (CRNs) due to the interference temperature constraint imposed by the primary receiver (PRx). Multi-hop relaying is an efficient strategy to increase the coverage area in scenarios with per node transmit power constraints. Cooperative multi-hop relaying with cluster of relays in each hop, can be employed to enhance the performance of CRNs by exploiting the broadcast nature of the wireless channel. In this dissertation, we present a detailed performance analysis of various path selection schemes for cooperative/cluster-based multi-hop CRNs with decode-and-forward (DF) relays. Both peak-power and peak-interference constraints are imposed on the transmit powers of SUs, and Rayleigh fading is assumed for the channels between various nodes present in the system.

At first, we analyze the performance of cooperative multi-hop CRNs with fixed DF relays using the optimal-path-selection. This scheme chooses a multi-hop path with the best end-to-end equivalent signal-to-noise-ratio (SNR). The optimal path selection requires global channel-state-information (CSI) for choosing the best path, which overburdens radio frequency chains of transceivers. In order to reduce the CSI overhead, an ad-hoc routing scheme called max-link-selection is studied. This scheme selects a path with the best received SNR in each hop except last two hops. For the final two hops of transmission, a path that maximizes the equivalent SNR of these hops is chosen. The performance of both these schemes is evaluated in terms of their outage probability, symbol-error-rate (SER), ergodic rate, and diversity order.

In underlay CRNs, with peak-interference-constraint, transmitting power of an SU is a function of its channel gain to the PRx, which is a random variable. By exploiting

this unique characteristic of CRNs, we propose and analyze a novel ad-hoc routing scheme for cooperative multi-hop CRNs with selective DF relays, which is termed as best last highest transmitting power rest (BLHTPR) scheme. Here at each hop, the relays whose received SNR exceed a predefined threshold form a set called as decoding set. In the BLHTPR scheme, a relay with best transmitting power is selected from each decoding set except in the last hop, whereas a relay with the best SNR to the destination is selected from the final decoding set. Next, we study the performance of a cooperative multi-hop CRN with best last arbitrary rest (BLAR) routing scheme that selects a relay arbitrarily from the decoding set in each hop except in the last hop, where a decoding relay with the best SNR to the destination is chosen as in the BLHTPR. We analyze the performance of both these schemes, and compare them with that of the max-link and optimal path selection schemes.

With serial multi-hop relaying, the number of time slots taken for conveying the source's data to the destination equals to the number of relaying hops. As a result, the data throughput of the multi-hop relaying declines with increasing number of hops. To circumvent the implied loss in data throughput due to multi-hop relaying while improving the coverage area, we propose two incremental relaying (IR) schemes with selective DF relays. The first scheme, namely, IR based highest SNR (IR-HSNR) scheme chooses a relay from each decoding set with best SNR to the PRx. The second scheme, referred to as the IR based highest transmit power (IR-HTP) protocol picks a decoding relay with highest available transmit power at each hop. For both of these protocols, it is assumed that a dedicated error free one bit feedback link is available from the destination to all other nodes in the considered system. This feedback bit informs whether the destination has received a sufficiently strong signal or not during the current relaying hop. The status of the feedback bit decides whether to use the relays in the succeeding hop or not. It is demonstrated through numerical results that the throughput performance of the IR-HSNR is superior to that of the IR-HTP, whereas the latter has lower implementation complexity. Furthermore, we show that throughputs of both these IR schemes outperform that of the existing relay selection schemes without IR.

सार

प्राथमिक रिसीवर (पीआरएक्स) द्वारा हस्तक्षेप तापमान बाधा लगाए जाने के कारण अंडरले संज्ञानात्मक रेडियो नेटवर्क (सीआरएनए) में माध्यमिक उपयोगकर्ताओं (एसयूएस) की प्रेषण शक्ति पर प्रतिबंध लगता है। मल्टी-हॉप रिलेइंग एक कुशल रणनीति है कवरेज क्षेत्र बढ़ाने कलिये जहाँ प्रेषण शक्ति की बाधाएँ हैं। हर हॉप में रिले क क्लस्टर नियोजित करने से और वायरलेस चैनल की प्रसारण प्रकृति का उपयोग करके सीआरएन का प्रदर्शन बढ़ाया जा सकता है इस शोध प्रबंध में, हम विभिन्न पथ चयन का विस्तृत प्रदर्शन विश्लेषण प्रस्तुत किया गया है सहकारी / क्लस्टर-आधारित बहु-हॉप सीआरएन के लिए डीकोड-एंड-फॉरवर्ड (डीएफ) योजनाएं के साथ। पीक पावर और पीक इंटरफेरेंस दोनों को लगाया गया है माध्यमिक उपयोगकर्ताओं की प्रेषण शक्ति पर और विभिन्न नोइस चैनलों के बीच रायलीघ फडिंग मानि गयी है।

सबसे पहले हमने सहकारी / क्लस्टर-आधारित बहु-हॉप सीआरएन के प्रदर्शन का विश्लेषण किया है फिक्स्ड डी फ योजन के साथ इष्टतम पथ का चयन उपयोग करके। यह योजना चुनती है एक मल्टी-हॉप पथ जिसका अंत-टू-एंड समकक्ष सिग्नल-टू-शोर-अनुपात (एसएनआर) सर्वोत्तम होता है। इष्टतम पथ चयन सर्वश्रेष्ठ पथ चुनने के लिए वैश्विक चैनल-स्टेटस-सूचना (सीएसआई) की आवश्यकता होती है, जो ट्रांसीवर की रेडियो फ्रीक्वेंसी चैन को ओवरबर्ड करता है। सीएसआई ओवरहेड को कम करने के लिए, अधिकतम-लिंक-चयन नामक एड-हॉक रूटिंग योजना का अध्ययन किया गया है। यह योजना एक पथ का चयन करती है, पिछले दो हॉप को छोड़कर प्रत्येक हॉप में सर्वश्रेष्ठ प्राप्त एसएनआर के उपयोग करके। अंतिम दो हॉप्स के लिए ट्रांसमिशन, एक पथ जो इन हॉप्स के समकक्ष एसएनआर को अधिकतम करता है, वह चुना जाता है। इन दोनों योजनाओं के प्रदर्शन का मूल्यांकन उनकी प्रतीक-त्रुटि दर (एसईआर), एरगोदिक दर, और डाइवर्सिटी आर्डर की संभावना के संदर्भ में किया गया है।

अंडरले सीआरएन में, पीक-हस्तक्षेप-बाधा के साथ, एक एसयू की शक्ति प्रेषण अपने चैनल का एक प्रोजेक्ट पीआरएक्स को हासिल करता है, जो एक यादृच्छिक चर है।

सीआरएन की इस अनूठी विशेषता का उपयोग करके, हम एक नया सहकारी बहु-हॉप सीआरएन आधारित अड हॉ-मार्ग रूटिंग योजना को प्रस्तुत कर रहे हैं, जिसे सर्वोत्तम उच्चतम ट्रांसमिटिंग पावर रेस्ट (बीएलएचटीपीआर) योजना कहा जाता है। यहां प्रत्येक हॉप जिस रिले का प्राप्त एसएनआर एक पूर्वनिर्धारित दहलीज से अधिक है, वह सेट बनाते हैं जिसे डीकोडिंग सेट कहा जाता है।

बीएलएचटीपीआर योजना में, सर्वोत्तम प्रेषण शक्ति वाला एक रिले का चयन किया जाता है प्रत्येक डिकोडिंग सेट से, आखिरी हॉप को छोड़कर, जबकि सर्वश्रेष्ठ एसएनआर के साथ एक रिले अंतिम डिकोडिंग सेट से गंतव्य का चयन किया जाता है। इसके बाद, हम सहकारी मल्टी-हॉप सीआरएन की सर्वश्रेष्ठ सहानुभूतिपूर्ण आराम (बीएलएआर) रूटिंग योजना के प्रदर्शन का अध्ययन करते हैं, इसमें प्रत्येक हॉप में डिकोडिंग सेट से मनमाने ढंग से रिले का चयन होता है, आखिरी हॉप को छोड़कर, जहां गंतव्य के लिए सर्वश्रेष्ठ एसएनआर के साथ एक डिकोडिंग रिले को चुना जाता है, जैसे की बीएलएआर योजना में होता है। हम इन दोनों योजनाओं के प्रदर्शन का विश्लेषण करते हैं, और उनकी तुलना अधिकतम लिंक और इष्टतम पथ चयन योजनाओं के साथ करते रहे हैं। सीरियल मल्टी-हॉप रिलेइंग के साथ डाटा ट्रांसफर करने के लिए टाइम स्लॉट्स की संख्या रिले नोड्स के बराबर होती है।

नतीजतन, होप्स की बढ़ती संख्या के साथ मल्टी-हॉप रिलेइंग की डेटा थ्रूपुट कम हो जाती है। बहु-हॉप रिलेइंग के कारण डेटा थ्रूपुट में अंतर्निहित हानि को रोकने के लिए और कवरेज क्षेत्र को सकल लिए, हम चुनिंदा डीएफ रिले के साथ दो वृद्धिशील रिलेइंग (आईआर) योजनाओं का प्रस्ताव दे रहे हैं। पहली योजना, अर्थात् आईआर आधारित उच्चतम एसएनआर (आईआर-एचएसएनआर) योजना पीआरएक्स को सर्वश्रेष्ठ एसएनआर के साथ प्रत्येक डिकोडिंग सेट से रिले चुनती है। दूसरी योजना, जिसे आईआर आधारित उच्चतम ट्रांसमिशन पावर (आईआर-एचटीपी) प्रोटोकॉल कहाँ जाता है, वह प्रत्येक हॉप में उच्चतम उपलब्ध ट्रांसमिट शक्ति वाला एक डिकोडिंग रिले चुनती है। इन दोनों प्रोटोकॉल के लिए, यह माना जाता है कि गंतव्य से सभी अन्य नोड्स को एक समर्पित त्रुटि मुक्त एक बिट फीडबैक लिंक उपलब्ध है। यह प्रतिक्रिया बिट सूचित करती है कि वर्तमान रिलेइंग हॉप में गंतव्य को पर्याप्त मजबूत सिग्नल प्राप्त हुआ है या नहीं। फीडबैक बिट की स्थिति का फैसला करती है कि रिले का उपयोग अगले हॉप के लिए करना है या नहीं। यह संख्यात्मक परिणामों के माध्यम से प्रदर्शित किया गया है की आईआर-एचएसएनआर का थ्रूपुट प्रदर्शन आईआर-एचटीपी से बेहतर है, जबकि उत्तरार्द्ध में कम कार्यान्वयन जटिलता है। इसके अलावा, हम इसे दिखाते हैं की इन दोनों आईआर योजनाओं के थ्रूपुट मौजूदा रिले चयन से बेहतर प्रदर्शन करते हैं।

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Abbreviations

AF	Amplify-and-forward
AWGN	Additive white Gaussian noise
BER	Bit error rate
BLAR	Best last arbitrary rest
CCI	Co-channel interference
CDF	Cumulative distribution function
CR	Cognitive radio
CRN	Cognitive radio network
CSI	Channel state information
DF	Decode-and-forward
DMT	Diversity multiplexing trade-off
i.i.d.	Independent and identically distributed
i.n.i.d.	Independent but not identically distributed
IR	Incremental relaying
IR-HSNR	Incremental relaying with highest signal-to-noise-ratio
IR-HTP	Incremental relaying with highest transmit power
MIMO	Multiple-input multiple-output
M -PSK	M -ary phase shift keying
M -QAM	M -ary quadrature amplitude modulation
MRC	Maximal ratio combining
PDF	Probability density function
PRx	Primary receiver
PTx	Primary transmitter

QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RF	Radio frequency
Rx	Receiver
SC	Selection combining
SER	Symbol error rate
SINR	Signal-to-interference-noise-ratio
SNR	Signal-to-noise Ratio
SRx	Secondary receiver
STBC	Space time block code
STx	Secondary transmitter
TAS/MRC	Transmit antenna selection/Maximum ratio combining
Tx	Transmitter