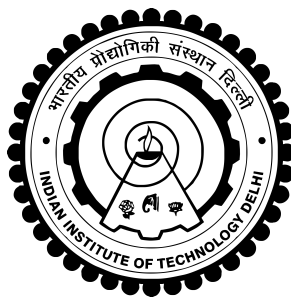


**PERFORMANCE ANALYSIS OF UNDERLAY
COGNITIVE RADIO NETWORKS WITH ENERGY
HARVESTING NODES**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JUNE 2018

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by

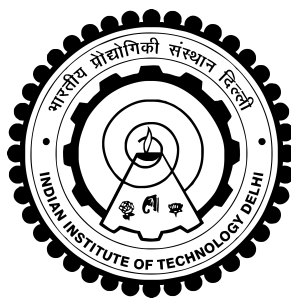
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submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2018

CERTIFICATE

This is to certify that the thesis titled **Performance Analysis of Underlay Cognitive Radio Networks with Energy Harvesting Nodes**, submitted by **Mr. Komal Janghel**, 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 my 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.

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ABSTRACT

Two major problems greatly impede ubiquitous deployment of wireless devices. The first relates to spectrum scarcity caused by a surge in the number of communication devices and types of data services. It is now widely accepted that cognitive radios, that allow licensed (primary) users to share their spectrum with the unlicensed (secondary) users show great promise in improving spectrum utilization and overcoming spectrum scarcity. Underlay type of cognitive radios, in particular, are being researched widely in recent years. The second major problem impeding the growth of wireless services relates to battery limitations and difficulty in replacing them. Energy harvesting has been suggested as a practical solution to this problem. While energy harvesting from ambient sources is possible, it has been demonstrated that harvesting energy using the signal transmitted by the source is practical and reliable. It is clear from the above that underlay cognitive radio with energy harvesting nodes is of practical interest. Since the performance of these systems is quite different from that of conventional energy harvesting systems, accurate analysis is important. Understanding how to optimize performance of these systems is vital. This thesis makes important contributions in analysis and optimization of performance of underlay cognitive radio links with energy harvesting nodes.

In the first contribution, the thesis examines a new framework that facilitates joint energy and spectrum sharing. In this framework, a multi-antenna primary transmitter communicating to its receiver via a relay shares excess energy (after ensuring adequate signal-to-noise ratio (SNR) at the relay) with a secondary transmitter, thereby enabling it to share the spectrum during the second hop of primary transmission. Design of a primary beamformer is discussed, and performance of the secondary system is analyzed. It is shown that judicious power allocation between the primary source and the relay is vital to achieving good secondary performance.

In the second contribution, a protocol is proposed that enables the secondary two-

hop network with an energy harvesting relay to attain good throughput by allowing the charging duration to vary with channel gains. It is well known that in a two-hop transmission with relay powered by source transmission, choosing the fixed charging duration optimally is very important to attain good performance. However, due to the large variation in the SNRs of the two hops in cognitive radio networks, and random nature of the energy harvested, the performance attained is often poor. One solution to this problem is the use of a variable charging time that depends on channel gains. A protocol is proposed in this chapter that facilitates this without requiring channel gains to be measured and passed between nodes. In the proposed scheme, energy is transmitted in small packets until the relay is sufficiently charged. An estimate of the number of energy packets is based on channel variances, though knowledge of second hop channel gain can result in throughput gains. It is shown that when the error in second-hop channel estimates is large, it is best to use the statistical average channel value to estimate the number of energy packets required.

In the third contribution, the two-hop cognitive underlay network is revisited, and importance of the direct channel in the analysis of the performance of such networks is brought out. It is argued that the nodes in such a network need to be in proximity for acceptable performance due to random nature of the energy harvested as well as random transmit powers of nodes. However, in all literature to date, it has been assumed that the direct link between source and destination is shadowed. In this thesis, the case when the direct and relayed signals are combined is considered. We demonstrate that relaying is advantageous in such links only when it possesses multiple antennas, which is quite unlike the situation in non-energy harvesting networks. Further, the performance of the incremental relaying protocol is analyzed, and it is shown to result in performance that is superior to direct signalling without a relay.

सार

दो प्रमुख समस्याएं बेतार (wireless) उपकरणों की सर्वव्यापी तैनाती में बाधा डालती हैं। पहला, संचार उपकरणों और डेटा सेवाओं के प्रकारों में वृद्धि के कारण स्पेक्ट्रम की कमी से संबंधित है। अब यह व्यापक रूप से स्वीकार किया जाता है कि संज्ञानात्मक रेडियो (cognitive radio), जो लाइसेंस प्राप्त (प्राथमिक) उपयोगकर्ताओं को अपने स्पेक्ट्रम को लाइसेंस रहित (द्वितीयक (secondary)) उपयोगकर्ताओं के साथ साझा करने की अनुमति देता है, स्पेक्ट्रम उपयोग में सुधार और स्पेक्ट्रम की कमी पर काबू पाने में बहुत बड़ा योगदान देता है। विशेष रूप से संज्ञानात्मक रेडियो के अंडरले (underlay) प्रकार का हाल के वर्षों में व्यापक रूप से शोध किया जा रहा है। बेतार सेवाओं के विकास को प्रभावित करने वाली दूसरी बड़ी समस्या बैटरी सीमाओं और उन्हें बदलने में कठिनाई से संबंधित है। इस समस्या के व्यावहारिक समाधान के रूप में ऊर्जा संचयन (energy harvesting) का सुझाव दिया गया है। जबकि परिवेश स्रोतों (ambient sources) से ऊर्जा की संचयन संभव है, यह दर्शाया गया है कि स्रोत द्वारा प्रेषित सिग्नल (signal) का उपयोग कर संचित (harvested) ऊर्जा व्यावहारिक और भरोसेमंद है। यह उपर्युक्त से स्पष्ट है कि ऊर्जा संचयन नोइस के साथ अंडरले संज्ञानात्मक रेडियो व्यावहारिक रुचि का है। चूंकि इन प्रणालियों का प्रदर्शन परंपरागत ऊर्जा संचयन प्रणाली से काफी अलग है, इसलिए सटीक विश्लेषण महत्वपूर्ण है। इन प्रणालियों के प्रदर्शन को अनुकूलित (optimize) करने के तरीके को समझना महत्वपूर्ण है। यह थीसिस ऊर्जा संचयन नोइस के साथ अंडरले संज्ञानात्मक रेडियो लिंक के प्रदर्शन के विश्लेषण और अनुकूलन (optimization) में महत्वपूर्ण योगदान देता है।

पहले योगदान में, थीसिस एक नई ढांचे की जांच करता है जो संयुक्त ऊर्जा और स्पेक्ट्रम साझा करने की सुविधा प्रदान करता है। इस ढांचे में, एक रिले के माध्यम से अपने रिसीवर को संचारित एक बहु एंटीना प्राथमिक ट्रांसमीटर एक अतिरिक्त द्वितीयक ट्रांसमीटर के साथ अतिरिक्त सिग्नल-टू-नोइस (signal-to-noise) अनुपात (SNR) सुनिश्चित करने के बाद, इस प्रकार प्राथमिक संचरण की दूसरी हॉप के दौरान स्पेक्ट्रम साझा करने में सक्षम बनाता है। प्राथमिक बीमफॉर्मर के डिजाइन पर चर्चा की जाती है, और द्वितीयक प्रणाली के प्रदर्शन का विश्लेषण किया जाता है। यह दिखाया गया है कि प्राथमिक स्रोत और रिले के बीच न्यायिक शक्ति आवंटन अच्छा द्वितीयक नेटवर्क के प्रदर्शन प्राप्त करने के लिए महत्वपूर्ण है।

दूसरे योगदान में, एक प्रोटोकॉल प्रस्तावित किया है जो चार्जिंग अवधि चैनल लाभ के साथ भिन्न होने की अनुमति देकर अच्छा थ्रूपुट प्राप्त करने के लिए ऊर्जा संचयन रिले के साथ द्वितीयक दो-हॉप नेटवर्क को सक्षम बनाता है। यह अच्छी तरह से ज्ञात है कि स्रोत संचरण द्वारा संचालित रिले के साथ दो-हॉप ट्रांसमिशन में, अच्छे प्रदर्शन को प्राप्त करने के लिए निश्चित चार्जिंग अवधि का चयन करना बहुत महत्वपूर्ण है। हालांकि, संज्ञानात्मक रेडियो नेटवर्क में दो हॉपों के एसएनआर में बड़ी भिन्नता और ऊर्जा की संचयन की यादृच्छिक (random) प्रकृति में बड़ी भिन्नता के चलते, प्रदर्शन प्राप्त अक्सर खराब होता है। इस समस्या का एक समाधान एक परिवर्तनीय चार्जिंग समय का उपयोग है जो चैनल लाभ पर निर्भर करता है। इस अध्याय में एक प्रोटोकॉल का प्रस्ताव है जो इसे चैनल लाभों को मापने और नोइस के बीच पारित होने की आवश्यकता के बिना सुविधा प्रदान करता है। प्रस्तावित योजना में, रिले पर्याप्त रूप से चार्ज होने तक ऊर्जा को छोटे पैकेट में प्रेषित किया

जाता है। ऊर्जा पैकेटों की संख्या का अनुमान चैनल भिन्नताओं पर आधारित है, हालांकि दूसरे हॉप चैनल लाभ के ज्ञान के माध्यम से थ्रूपुट लाभ हो सकता है। यह दिखाया गया है कि जब दूसरे-हॉप चैनल अनुमानों में त्रुटि बड़ी होती है, तो आवश्यक आवश्यक ऊर्जा पैकेट की संख्या का आकलन करने के लिए सांख्यिकीय औसत चैनल मान का उपयोग करना सबसे अच्छा होता है।

तीसरे योगदान में, दो-हॉप संज्ञानात्मक अंडरले नेटवर्क का पुनरीक्षण किया जाता है, और ऐसे नेटवर्क के प्रदर्शन के विश्लेषण में प्रत्यक्ष चैनल का महत्व लाया गया है। यह तर्क दिया है कि इस तरह के नेटवर्क में नोड्स को ऊर्जा संचयन की यादृच्छिक प्रकृति के साथ-साथ नोड्स की यादृच्छिक प्रेषण शक्तियों (transmit powers) के कारण स्वीकार्य प्रदर्शन के लिए निकटता में होना चाहिए। हालांकि, आज तक सभी साहित्य में, यह माना गया है कि स्रोत और गंतव्य के बीच सीधा लिंक छायांकित है। इस थीसिस में, जब प्रत्यक्ष और रिलेड सिग्नल संयुक्त होते हैं तो वह मामला माना जाता है। हम दर्शाते हैं कि रिलेइंग केवल ऐसे लिंक में फायदेमंद है जब इसमें कई एंटेना होते हैं, जो गैर-ऊर्जा संचयन नेटवर्क की स्थिति के विपरीत है। इसके अलावा, वृद्धिशील रिलेइंग प्रोटोकॉल का प्रदर्शन विश्लेषण किया है, और यह परिणाम में दिखाया है जो रिले के बिना सीधे सिग्नलिंग से बेहतर होता है।

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ABBREVIATIONS

AEC	Average energy consumption
AF	Amplify and forward
AWGN	Additive white Gaussian noise
bpcu	Bits per-channel use
CCDF	Complimentary cumulative distribution function
CCRN	Cooperative cognitive radio network
CDF	Cumulative distribution function
CDMA	Code-division multiple access
CRN	Cognitive radio network
CGI	Channel gain information
D	Source node in point-to-point and cooperative communication
dB	Decibel
DF	Decode and forward
DoF	Degree of freedom
DSA	Dynamic spectrum access
EH	Energy harvesting
IoT	Internet of things
IR	Incremental relaying
ITL	Interference temperature limit
LoS	Line-of-sight
MIMO	Multi-input and multi-output
MRC	Maximal ratio combining
MRT	Maximal ratio transmission
NOMA	Non-orthogonal multiple access
PD	Primary destination
PDF	Probability density function
PN	Primary network
PR	Primary relay

PS	Power-splitting
PT	Primary transmitter
PU	Primary user
QoS	Quality of service
R	Relay node in cooperative communication
RAS	Receive antenna selection
RF	Radio frequency
S	Source node in point-to-point and cooperative communication
SD	Secondary destination
SDR	Software defined radio
SINR	Signal-to-interference plus noise ratio
SN	Secondary network
SNR	Signal-to-noise ratio
SR	Secondary relay
SS	Secondary source
SU	Secondary user
SWIPT	Simultaneous wireless and information transmission
TAS	Transmit antenna selection
TS	Time-switching

NOTATION

$(\cdot)^*$	Conjugation
$(\cdot)^H$	Hermitian transpose
$ \cdot $	Absolute value
$\ \cdot\ $	Norm of a vector
$\mathbf{x}^\perp$	Orthogonal vector to $\mathbf{x}$
$\exp(\lambda)$	Exponential distribution with parameter λ
$\mathcal{CN}(0, a)$	Circular normal distribution with mean 0 and variance a
$\Gamma(\cdot, \cdot)$	Upper Incomplete Gamma function, $\Gamma(n, x) = \int_x^\infty \frac{e^{-xt}}{t^{n-1}} dt \quad [1, (8.350.2)]$
$\gamma(\cdot, \cdot)$	Lower Incomplete Gamma function, $\gamma(n, x) = \int_x^\infty \frac{e^{-xt}}{t^{n-1}} dt \quad [1, (8.350.1)]$
$K_n(\cdot)$	n th order modified Bessel function of second kind, $K_n(x) = \frac{1}{2} \left(\frac{x}{2}\right)^n \int_0^\infty t^{n-1} e^{-\frac{1}{t} - (\frac{x}{2})^2 t} dt \quad [1, (3.471.12)]$
$\langle \mathbf{x}, \mathbf{y} \rangle$	Inner product between vectors $\mathbf{x}$ and $\mathbf{y}$
$I_o(\cdot)$	Modified Bessel function of zeroth order, $I_o(x) = \frac{1}{\pi} \int_0^\pi e^{x \cos t} dt \quad [1, (3.339)]$
$\mathbb{E}_X$	Expectation over random variable X
$E_i(\cdot)$	Exponential integral for real non zero values, $E_i(x) = -\oint_{-x}^\infty t^{-1} e^{-t} dt \quad [2, (5.1.2)]$
$E_n(\cdot)$	Generalized exponential integral of order n , $E_n(x) = \int_1^\infty \frac{e^{-xt}}{t^n} dt \quad [2, (5.1.4)]$
$\lfloor x \rfloor$	Floor value of x (integer part of x)
$\lceil x \rceil$	Smallest integer greater than x
$F_X(x)$	Cumulative distributive function (CDF) of random variable X
$f_X(x)$	Probability density function of random variable X
$F_{X Y}(x)$	CDF of X given Y
$U(\cdot)$	Unit-step function
τ	Throughput of the network in bit per channel use (bpcu)
R_s	Secondary network transmission bit rate (in bpcu)
R_p	Primary network transmission bit rate (in bpcu)
γ_{th}	Target SNR threshold ($\gamma_{th} = 2^{R_t} - 1$), where R_t is the target rate
ρ	Correlation coefficient between actual and estimated channel
α	Generalized energy harvesting factor ($0 \leq \alpha \leq 1$)
α_{ts}	Energy harvesting factor for time-switching case ($0 \leq \alpha_{ts} \leq 1$)
α_{ps}	Energy harvesting factor for power-splitting case ($0 \leq \alpha_{ps} \leq 1$)
C	Ergodic Capacity (in bpcu)

η	Energy harvesting efficiency of an EH node
Γ_a	Signal-to-noise ratio at node A
E	Energy
P	Power
I	Interference temperature limit at primary destination
$\mathcal{E}$	Average Energy Consumption
n_a	Additive noise at node A
$Q(\cdot, \cdot)$	Marcum-Q function, $Q(a, b) = \int_b^\infty x \exp\left(-\frac{x^2 + a^2}{2}\right) dx$ [3, (1)]
$Q(\cdot)$	Q-function, $Q(x) = \frac{1}{2\pi} \int_x^\infty \exp\left(-\frac{u^2}{2}\right) dx$, [2, (7.1.2)]
$\mathbb{D}$	Diversity order of the network
ε	Path-loss factor between two nodes
$\hat{\kappa}$	Charging threshold correction factor for the case of imperfect SR-SD channel
$\bar{\kappa}$	Charging threshold correction factor for the case of only statistical SR-SD channel knowledge
d'_{ab}	Euclidean distance between nodes A and B
d'_o	Reference distance for the antenna far field
d_{ab}	Normalized distance between nodes A and B d'_{ab}/d'_o
x_s	Message signal at node S
y_{ab}	Received signal at node B which is transmitted from node A
$1/\lambda_{ab}$	Variance of the channel between nodes A and B, $\lambda_{ab} = d_{ab}^\varepsilon$
N_o	Noise variance (power) at destination node