

**OPTIMIZATION OF NETWORKS WITH ENERGY
HARVESTING RELAYS**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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OPTIMIZATION OF NETWORKS WITH ENERGY HARVESTING RELAYS

by

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DEPARTMENT OF ELECTRICAL ENGINEERING

submitted

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CERTIFICATE

This is to certify that the thesis titled **Optimization of Networks with Energy Harvesting Relays**, submitted by Mr. **Modem Sudhakar**, 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.

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ABSTRACT

Fifth generation (5G) communication systems are envisioned to achieve high data rate, provide enhanced coverage, enable higher spectral efficiency, achieve high energy efficiency, and ensure long life-time of all battery operated nodes. To achieve these ambitious goals, cooperative communication and energy harvesting (EH) are expected to play major roles. EH is already emerging as an attractive option to increase lifetime of battery operated nodes. While EH from ambient radio frequency (RF) is being considered, EH from signal transmitted by the source is the one that shows the most promise due to its reliability. While performance of cooperative networks has been analyzed, that of cooperative links with EH relays has received comparatively little research attention. Deriving expressions for performance of such links, and optimization of their performance is clearly of vital importance. The problem addressed in this thesis is analysis and optimization of performance of cooperative communication networks with EH relays.

We analyze outage, throughput, ergodic rate, and symbol error rate (SER) performance of spectrally efficient two-way relay networks with an EH relay, and show how their performance can be optimized. We analyze performance with time-switching relaying (TSR) and power-splitting relaying (PSR). We present closed-form expressions for these parameters in important cases. We show that relay location and EH parameter need to be jointly optimized for best performance.

We then investigate throughput, ergodic rate and SER performance of cognitive underlay two-way networks with a PSR based EH relay, and develop important insights into their performance. In such networks, where both terminals transmit simultaneously, apportioning of the interference temperature threshold (ITL) is of importance. We show that the ITL apportioning parameter (ITAP) and the EH parameter can be optimized separately, and derive expressions for these. We show that an ITAP of 0.5 maximizes sum ergodic rate of such networks. In two-way networks with EH relays,

energy can be drawn from either both sources (dual-link or DL), the one with the best link to the relay, or any one fixed source. We analyze performance of two-way underlay networks based on DL TSR protocol, and compare performance of different schemes.

Due to fading, the amount of energy harvested varies widely, thereby degrading average performance of links with EH relays. We suggest a framework where a supplementary battery augments energy harvested in the super capacitor. Several new optimization problems arise. We show how use of a small amount of battery energy can significantly improve performance of two-hop links with EH relays. We demonstrate that careful optimization of the EH parameter can significantly enhance throughput. For networks with a constant throughput requirement, we show how the amount of battery energy drawn and the EH parameter need to be carefully optimized. We show how channel knowledge can lead to significant saving of battery energy. We then analyze performance of two-way relays in such a framework, and study their optimizations. We show how choosing the EH parameter based on channel knowledge can lead to higher throughput. We demonstrate that use of channel knowledge to determine energy drawn from the battery can lead to significant energy savings. The insights drawn as well as the optimizations performed are of significant importance to system designers.

सार

पांचवीं पीढ़ी (5 जी) संचार प्रणालियां उच्च डाटा दर हासिल करने, उन्नत कवरेज प्रदान करने, उच्च वर्णक्रमीय (स्पेक्ट्रम) दक्षता को सक्षम करने, उच्च ऊर्जा दक्षता प्राप्त करने और सभी बैटरी संचालित नोड्स के लंबे जीवन-काल को सुनिश्चित करने के लिए कल्पना की जाती हैं। इन महत्वाकांक्षी लक्ष्यों को प्राप्त करने के लिए, सहकारी संचार (कोआपरेटिव) और ऊर्जा संचयन (ईएच) को प्रमुख भूमिका निभाने की उम्मीद है। ईएच पहले से ही बैटरी संचालित नोड्स के जीवनकाल को बढ़ाने के लिए एक आकर्षक विकल्प के रूप में उभर रहा है। जबकि परिवेशी (एम्बिएंट) आकाशवाणी आवृत्ति (आरएफ) से ईएच माना जा रहा है, प्रेषित संकेत स्रोत द्वारा ईएच है जिसकी विश्वसनीयता के कारण सबसे वादा दिखाता है। सहकारी नेटवर्क के प्रदर्शन का विश्लेषण किया गया है, जबकि ईएच रिले के साथ सहकारी लिंक की तुलनात्मक रूप से थोड़ा शोध ध्यान प्राप्त हुआ है। इस तरह के लिंक के निष्पादन के लिए व्यक्त अभिव्यक्ति, और उनके प्रदर्शन का अनुकूलन स्पष्ट रूप से महत्वपूर्ण महत्व का है। इस थीसिस में संबोधित समस्या ईएच रिले के साथ सहकारी संचार नेटवर्क के प्रदर्शन का विश्लेषण और अनुकूलन है।

हम एएच रिले के साथ वर्णक्रमीयता कुशल दो-तरफा रिले नेटवर्क के आउटेज, थ्रूपुट, एर्गोडिक रेट और सिग्नल त्रुटि दर (एसईआर) के प्रदर्शन का विश्लेषण करते हैं और यह दिखाते हैं कि उनका प्रदर्शन कैसे अनुकूलित किया जा सकता है। हम समय-स्विचिंग रिलेइंग (टीएसआर) और पावर-स्प्लिटिंग रिलेइंग (पीएसआर) के साथ प्रदर्शन का विश्लेषण करते हैं। महत्वपूर्ण मामलों में हम इन मापदंडों के लिए क्लोज-फॉर्म एक्सप्रेशन प्रस्तुत करते हैं। हम बताते हैं कि सर्वोत्तम प्रदर्शन के लिए रिले स्थान और ईएच पैरामीटर को संयुक्त रूप से अनुकूलित किया जाना चाहिए।

हम फिर पीआरआर आधारित ईएच रिले के साथ संज्ञानात्मक (कॉग्निटिव) अंडरले दो-तरफा नेटवर्क के थ्रूपुट, एर्गोडिक रेट और एसईआर प्रदर्शन की जांच करते हैं, और उनके प्रदर्शन में महत्वपूर्ण अंतर्दृष्टि विकसित करते हैं। ऐसे नेटवर्क में, जहां दोनों टर्मिनलों को एक साथ संचारित किया जाता है, हस्तक्षेप तापमान सीमा (आईटीएल) को विभाजित करना महत्व का है। हम दिखाते हैं कि आईटीएल विभेदित पैरामीटर (आईटीएपी) और ईएच पैरामीटर अलग से अनुकूलित किया जा सकता है, और इन के लिए अभिव्यक्तियां प्राप्त कर सकते हैं। हम बताते

हैं कि 0.5 के आईटीएपी इस तरह के नेटवर्क की राशि को एगोडिक दर को अधिकतम करता है। ईएच रिले के साथ दो-तरफ़ा नेटवर्क में, ऊर्जा दोनों ओर के स्रोत से (दोहरे लिंक या डीएल), या फिर रिले के सर्वश्रेष्ठ लिंक या किसी एक निश्चित स्रोत से दोहन की जा सकती है हम डीएल टीएसआर प्रोटोकॉल पर आधारित दो-तरफ़ा अंडरले नेटवर्क के प्रदर्शन का विश्लेषण करते हैं और विभिन्न योजनाओं के प्रदर्शन की तुलना करते हैं।

अवसाद (फेडिंग) के कारण ,संचित ऊर्जा की मात्रा का व्यापक रूप से फैलाव होता है, जिससे ईएच रिले के साथ लिंक का औसत प्रदर्शन घटता है। हम एक रूपरेखा का सुझाव देते हैं जहां एक पूरक बैटरी सुपर संधारित्र में ऊर्जा का उत्पादन करती है। कई नई अनुकूलन समस्याएं पैदा होती हैं। हम दिखाते हैं कि छोटी ऊर्जा की एक छोटी राशि का उपयोग ईएच रिले के साथ दो हॉप लिंक के प्रदर्शन में काफी सुधार कर सकता है। हम यह दर्शाते हैं कि ईएच पैरामीटर का सावधानीपूर्वक अनुकूलन, थ्रूपुट को काफी बढ़ा सकता है। स्थिर थ्रूपुट आवश्यकता के साथ नेटवर्क के लिए, हम दिखाते हैं कि बैटरी की ऊर्जा की मात्रा कैसे दोहन की गई और ईएच पैरामीटर को ध्यान से अनुकूलित किया जाना चाहिए। हम बताते हैं कि चैनल का ज्ञान कैसे बैटरी ऊर्जा की महत्वपूर्ण बचत कर सकता है। हम इस तरह के ढांचे में दो-तरफ़ा रिले के प्रदर्शन का विश्लेषण करते हैं, और उनके अनुकूलन का अध्ययन करते हैं। हम दिखाते हैं कि चैनल ज्ञान के आधार पर ईएच पैरामीटर को कैसे चुनना उच्चतर थ्रूपुट से आगे बढ़ सकता है। हम यह दर्शाते हैं कि बैटरी से तैयार की जाने वाली ऊर्जा को निर्धारित करने के लिए चैनल ज्ञान का उपयोग महत्वपूर्ण ऊर्जा बचत का कारण बन सकता है। प्रदर्शन किए गए अंतर्दृष्टि के साथ-साथ सिस्टम ऑप्टिमाइज़ेशन सिस्टम डिज़ाइनर के लिए महत्वपूर्ण महत्व हैं।

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ABBREVIATIONS

5G	Fifth generation
AF	Amplify-and-forward
ANC	Analog network coding
AWGN	Additive white Gaussian noise
BAN	Body area network
BC	Broadcasting channel
CDF	Cumulative distribution function
CR	Cognitive radios
CSI	Channel state information
DF	Decode-and-forward
DL	Dual link
DMT	Diversity multiplexing trade-off
EH	Energy harvesting
i.i.d.	Independent and identically distributed
IoT	Internet-of-things
ITAP	Interference temperature apportioning parameter
ITL	Interference temperature limit
MAC	Multiple access channel
MIMO	Multi-input multi-output
MRT	Maximum ratio transmission
PDF	Probability density function
PN	Primary network
PSR	Power-splitting relaying
SBL	Single best link
SER	Symbol error rate
SFL	Single Fixed link
RF	Radio frequency
SN	Secondary network

SNR	Signal-to-noise ratio
SSER	Sum symbol error rate
TSR	Time-switching relaying
TWR	Two-way relaying

NOTATION

$ \cdot $	Absolute value
E_b	Battery energy
$\mathcal{CN}(\mu, \Omega)$	Circular complex Gaussian distribution with mean μ and variance Ω
$(\cdot)^\dagger$	Conjugate transpose
η	Energy harvesting circuit efficiency
P_{th}	Energy harvesting circuit sensitivity
\mathcal{R}	Ergodic rate
$(\cdot)_{\mathcal{R}}^c$	Ergodic rate optimum parameter value based on instantaneous channel values
$(\cdot)_{\mathcal{R}}^s$	Ergodic rate optimum parameter value based on statistical channel values
$\psi(\cdot)$	Euler psi function [1, 8.365.4]
$\mathbf{E}[\cdot]$	Expectation operator
$\mathbf{E}_X[\cdot]$	Expectation operation over variable X
$\mathbb{E}_n(\cdot)$	Exponential integral function of order n , $\mathbb{E}_n(z) = \int_1^\infty \frac{e^{-zt}}{t^n} dt$ [2, 5.1.4]
$\mathcal{Q}(\cdot)$	Gaussian \mathcal{Q} function
Q_e	Harvested energy
ϑ	Interference apportioning parameter
$\ \cdot\ $	l_2 -norm
$\gamma(\cdot, \cdot)$	Lower incomplete Gamma function, $\gamma(n, x) = \int_0^x e^{-t} t^{n-1} dt$ [1, 8.350.1]
$o(\cdot)$	Order of
\mathcal{P}_{out}	Outage
β	Power-splitting relaying parameter
\Pr	Probability of event
\mathcal{P}_s	Symbol error rate
T	Time frame of information block
α	Time-switching relaying parameter
τ	Throughput
$(\cdot)_{\tau}^c$	Throughput optimum parameter value based on instantaneous channel values
$(\cdot)_{\tau}^s$	Throughput optimum parameter value based on statistical channel values
$(\cdot)^t$	Transpose
$\Gamma(\cdot, \cdot)$	Upper incomplete Gamma function, $\Gamma(n, x) = \int_x^\infty e^{-t} t^{n-1} dt$ [1, 8.350.2]
σ^2	Variance of additive white Gaussian noise