PERFORMANCE OF SPECTRALLY-EFFICIENT SIGNALLING TECHNIQUES IN NETWORKS WITH BATTERY-ASSISTED ENERGY HARVESTING NODES

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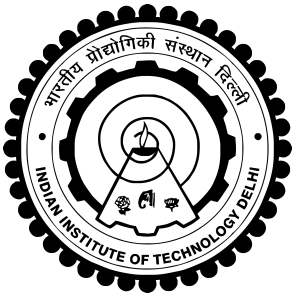

DEPARTMENT OF ELECTRICAL ENGINEERING
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by

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DEPARTMENT OF ELECTRICAL ENGINEERING

submitted

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CERTIFICATE

This is to certify that the thesis titled **PERFORMANCE OF COMMUNICATION NETWORKS WITH SPECTRALLY EFFICIENT BATTERY-ASSISTED ENERGY HARVESTING NODES**, submitted by **Kamal Agrawal**, 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. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

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

Future generation wireless networks are required to support high data rates and massive connectivity while ensuring an enormous reduction in energy consumption. The inclusion of the Internet of Things (IoT) and machine-to-machine (M2M) communication in fifth generation (5G) networks has increased the need to prolong the battery lifetimes of low-power machine-type devices (MTDs). To avoid frequent battery replacements, harvesting energy from RF signals to implement self-sustaining communication nodes is clearly well motivated. Unfortunately, the harvested energy is often quite small and random, which lowers the reliability of communication links with such energy harvesting (EH) nodes. Storing energy in batteries or super-capacitors until there is sufficient energy to transmit is a solution. However, rechargeable batteries make devices more complex and expensive besides increasing their form factor, while super-capacitors cannot store charge for a long time. Moreover, storing energy this way can increase latency in communications. Such self-sustaining nodes will be the future as low power signalling techniques are developed. Currently however, the energy requirement of nodes is too large to be met by energy harvesting with acceptable QoS. For these reasons, augmenting the harvested energy with as little battery energy as possible is a promising alternative for the immediate future, and can ensure increased battery life while simultaneously attaining the desired quality of service (QoS). The added battery energy helps in overcoming the problem of the random nature of the harvested energy. Such battery-assisted energy harvesting nodes can prolong battery lifetimes, and are immediately realizable. However, such battery-assisted EH nodes need careful optimization to ensure best throughput and energy efficiency. Technologies like full-duplex relays (FDRs) and non-orthogonal multiple access (NOMA) are proposed for achieving the goals of higher spectrum efficiency (SE) and massive connectivity. New standards for 5G suggest the use of IoT devices and MTDs with a large lifetime and enhanced connectivity. To realize these goals, understanding how to optimize NOMA and FDR networks with battery-assisted EH nodes is essential. However, this has never been attempted before. It is noted that in such networks, since battery energy consumption is of concern, node-

level energy efficiency is of importance in addition to system-level energy efficiency.

The main objective of this thesis is the analysis of performance and optimization of battery-assisted EH nodes in different networks so as to improve the QoS in terms of SE and energy efficiency (EE). In battery-assisted EH nodes, the precise battery energy management scheme used influences the amount of battery energy consumed. A fixed battery energy (FBE) scheme in which a fixed amount of battery energy is drawn in each symbol interval is taken up first because of its low implementation complexity. The performance of a dual-hop cooperative network with a battery-assisted EH half-duplex (HD) relay is analyzed assuming the presence of a direct channel from the source to the destination. In this context, the performance of selective decode-and-forward and incremental relaying schemes is analyzed. The importance of optimal choice of EH parameters is also brought out for throughput maximization and battery energy savings. Next, to further improve the SE, a dual-hop FD cooperative network is studied. Considering decode-and-forward (DF) and amplify-and-forward (AF) relaying at the FD relay, expressions are derived for the throughput with time-switching (TS) and power-splitting (PS) EH protocols. In the case of FD relaying, it is shown that a unique battery energy value exists that maximizes the throughput. Expressions are derived for the optimal TS/PS parameters for desired target throughput requirement so as to minimize the average battery energy consumption.

Use of EH nodes in cooperative NOMA (C-NOMA) and FD relaying based NOMA networks can enhance both EE and SE to a great extent. The performance of a C-NOMA network in which a battery-assisted EH FD near user (NU) assists in information transfer to multiple far users (FUs) is investigated. The NU is allowed to switch to a non-cooperative mode in a hybrid scheme to ensure that its own performance is not degraded due to the FU. Considering nonlinear EH at the NU, expressions are derived for the outage probability and throughput at NU and FU. Use of this hybrid scheme provides higher immunity to residual self-interference and higher EE. To further increase the range of C-NOMA, an R-NOMA framework is studied where the base station directly communicates to the NU, while a dedicated FD relay is used for forwarding information to the FU. Considering PS and TS EH protocols, performance is analyzed in terms of the outage probability and throughput. The performance of FU is maximized by optimally choosing the TS/PS parameter while ensuring the desired target QoS at NU. To further improve energy efficiency, a new dynamic battery energy (DBE)

scheme is proposed in which the battery energy drawn depends on the amount of harvested energy. It is demonstrated that using the DBE scheme to manage the battery energy ensures higher energy efficiency than is possible with the FBE scheme.

In wireless sensor networks (WSN) and body area networks, it is often desired that a node assists other nodes in its vicinity. The battery lifetime and communication range of such nodes are quite limited. Using EH at the relaying node can ensure that its battery lifetime is not decreased significantly. In many practical systems, the instantaneous CSI can be estimated with reasonable accuracy. It is shown in this thesis that the availability of instantaneous CSI can help the self-sustaining EH devices in prolonging their battery life significantly. To investigate the impact of CSI knowledge in a two-hop FD relay framework, a dynamic TS protocol is proposed with intelligent battery management at the relay. Performance of the static and CSI dependent (dynamic) TS EH protocols is analyzed in terms of throughput and average battery energy consumption. Use of dynamic TS provides substantial performance gains for both FBE and DBE energy management schemes over the static TS scheme. Also, by optimally choosing the TS EH parameter, the dynamic TS with DBE achieves enormous battery energy savings at the relay.

In view of the rapid growth in low-power devices in communication networks, the insights developed in this thesis are quite valuable to system designers for optimizing the throughput performance and battery lifetime.

सार

ऊर्जा खपत में भारी कमी सुनिश्चित करते हुए उच्च डेटा दरों और बड़े पैमाने पर कनेक्टिविटी का समर्थन करने के लिए भविष्य की पीढ़ी के वायरलेस नेटवर्क की आवश्यकता होती है। पांचवीं पीढ़ी (5जी) नेटवर्क में इंटरनेट ऑफ थिंग्स (आईओटी) और मशीन-टू-मशीन (एम 2 एम) संचार के समावेश ने कम शक्ति वाले मशीन-प्रकार के उपकरणों (एमटीडी) की बैटरी जीवनकाल को लंबा करने की आवश्यकता को बढ़ा दिया है। लगातार बैटरी प्रतिस्थापन से बचने के लिए, आत्म-टिकाऊ संचार नोड्स को लागू करने के लिए आरएफ संकेतों से ऊर्जा की कटाई स्पष्ट रूप से अच्छी तरह से प्रेरित है। दुर्भाग्य से, कटाई की गई ऊर्जा अक्सर काफी छोटी और यादृच्छिक होती है, जो इस तरह के ऊर्जा कटाई (ईएच) नोड्स के साथ संचार लिंक की विश्वसनीयता को कम करती है। जब तक संचारित करने के लिए पर्याप्त ऊर्जा नहीं होती है, तब तक बैटरी या सुपर-कैपेसिटर में ऊर्जा संग्रहीत करना एक समाधान है। हालांकि, रिचार्जेबल बैटरी अपने फॉर्म फैक्टर को बढ़ाने के अलावा डिवाइस को अधिक जटिल और महंगा बनाती है, जबकि सुपर-कैपेसिटर लंबे समय तक चार्ज स्टोर नहीं कर सकते हैं। इसके अलावा, इस तरह से ऊर्जा का भंडारण संचार में विलंबता को बढ़ा सकता है। कम बिजली सिग्नलिंग तकनीक विकसित करने के रूप में इस तरह के आत्म-टिकाऊ नोड्स भविष्य होगा। फिलहाल हालांकि, नोड्स की ऊर्जा आवश्यकता स्वीकार्य क्यूओएस के साथ ऊर्जा कटाई से पूरी होने के लिए बहुत बड़ी है। इन कारणों से, जितनी संभव हो उतनी कम बैटरी ऊर्जा के साथ कटाई की गई ऊर्जा को बढ़ाना तत्काल भविष्य के लिए एक आशाजनक विकल्प है, और एक साथ सेवा (क्यूओएस) की वांछित गुणवत्ता प्राप्त करते हुए बैटरी जीवन में वृद्धि सुनिश्चित कर सकते हैं। अतिरिक्त बैटरी ऊर्जा कटी हुई ऊर्जा की यादृच्छिक प्रकृति की समस्या को दूर करने में मदद करती है। इस तरह की बैटरी-सहायता ऊर्जा कटाई नोड्स बैटरी जीवनकाल को बढ़ा सकते हैं, और तुरंत वसूली योग्य हैं। हालांकि, ऐसे बैटरी-सहायता वाले ईएच नोड्स को सर्वोत्तम थ्रूपुट और ऊर्जा दक्षता सुनिश्चित करने के लिए सावधानीपूर्वक अनुकूलन की आवश्यकता होती है। उच्च स्पेक्ट्रम दक्षता (एसई) और बड़े पैमाने पर कनेक्टिविटी के लक्ष्यों को प्राप्त करने के लिए फुल-डुप्लेक्स रिले (एफडीआर) और नॉन-ऑर्थोगोनल मल्टीपल एक्सेस (एनओएमए) जैसी प्रौद्योगिकियों का प्रस्ताव है। 5जी के लिए नए मानकों में बड़े जीवनकाल और बढ़ी हुई कनेक्टिविटी के साथ आईओटी उपकरणों और एमटीडी के उपयोग का सुझाव दिया गया है। इन लक्ष्यों को महसूस करने के लिए, बैटरी-सहायता वाले ईएच नोड्स के साथ नोमा और एफडीआर नेटवर्क को अनुकूलित करने का तरीका समझना आवश्यक है। हालांकि इससे पहले कभी ऐसा प्रयास नहीं किया गया। यह ध्यान दिया जाता है कि इस तरह के नेटवर्क में, चूंकि बैटरी ऊर्जा की खपत चिंता का विषय है, इसलिए सिस्टम-स्तरीय ऊर्जा दक्षता के अलावा नोड-स्तरीय ऊर्जा दक्षता का महत्व है।

इस थीसिस का मुख्य उद्देश्य विभिन्न नेटवर्कों में बैटरी की मदद से ईएच नोड्स के प्रदर्शन और अनुकूलन का विश्लेषण है ताकि एसई और ऊर्जा दक्षता (ईई) के संदर्भ में क्यूओएस में सुधार किया जा सके। बैटरी की मदद से ईएच नोड्स में, सटीक बैटरी ऊर्जा प्रबंधन योजना का उपयोग बैटरी ऊर्जा की खपत की मात्रा को प्रभावित करता है। एक निश्चित बैटरी ऊर्जा (एफबीई) योजना जिसमें प्रत्येक प्रतीक अंतराल में बैटरी ऊर्जा की एक निश्चित राशि खींची जाती है, इसकी कम कार्यान्वयन जटिलता के कारण पहले ली जाती है। एक बैटरी की मदद से ईएच आधा द्वैध (एचडी) रिले के साथ एक दोहरी हॉप सहकारी नेटवर्क के प्रदर्शन स्रोत से गंतव्य के लिए एक प्रत्यक्ष चैनल की उपस्थिति मानते हुए विश्लेषण किया है। इस संदर्भ में, चयनात्मक डिकोड-एंड-फॉरवर्ड और वृद्धिशील रिलेइंग योजनाओं के प्रदर्शन का विश्लेषण किया जाता है। ईएच मापदंडों के इष्टतम विकल्प के महत्व को भी थ्रूपुट अधिकतमकरण और बैटरी ऊर्जा बचत के लिए सामने लाया गया है। आगे, एसई में और सुधार करने के लिए, एक दोहरी हॉप एफडी सहकारी

नेटवर्क का अध्ययन किया जाता है। एफडी रिले पर डीकोड-एंड-फॉरवर्ड (डीएफ) और एम्पलीफाइड-एंड-फॉरवर्ड (एएफ) रिले को ध्यान में रखते हुए, समय-स्विचिंग (टीएस) और पावर-स्प्लिटिंग (पीएस) ईएच प्रोटोकॉल के साथ थ्रूपुट के लिए अभिव्यक्ति प्राप्त की जाती है। एफडी रिलेइंग के मामले में, यह दिखाया गया है कि एक अद्वितीय बैटरी ऊर्जा मूल्य मौजूद है जो थ्रूपुट को अधिकतम करता है। अभिव्यक्तियां वांछित लक्ष्य थ्रूपुट आवश्यकता के लिए इष्टतम टीएस / पीएस मापदंडों के लिए ली गई हैं ताकि औसत बैटरी ऊर्जा खपत को कम किया जा सके।

सहकारी नोमा (सी-नोमा) और एफडी रिलेइंग आधारित नोमा नेटवर्क में ईएच नोड्स का उपयोग ईई और एसई दोनों को काफी हद तक बढ़ा सकता है। एक सी-नोमा नेटवर्क के प्रदर्शन जिसमें उपयोगकर्ता (एनयू) के पास एक बैटरी-सहायता प्राप्त ईएच एफडी कई दूर उपयोगकर्ताओं (एफयू) को सूचना हस्तांतरण में सहायता करता है, की जांच की जाती है। एनयू को हाइब्रिड योजना में गैर-सहकारी मोड पर स्विच करने की अनुमति है ताकि यह सुनिश्चित किया जा सके कि एफयू के कारण अपना प्रदर्शन खराब न हो। एनयू पर नॉनलाइनियर ईएच को ध्यान में रखते हुए, अभिव्यक्तियाँ एनयू और एफयू पर आउटेज संभावना और थ्रूपुट के लिए ली गई हैं। इस हाइब्रिड योजना का उपयोग अवशिष्ट स्व-हस्तक्षेप और उच्च ईई के लिए उच्च प्रतिरक्षा प्रदान करता है। सी-नोमा की सीमा को और बढ़ाने के लिए, एक आर-नोमा फ्रेमवर्क का अध्ययन किया जाता है जहां बेस स्टेशन सीधे एनयू से संवाद करता है, जबकि एक समर्पित एफडी रिले का उपयोग एफयू को जानकारी अग्रेषित करने के लिए किया जाता है। पीएस और टीएस ईएच प्रोटोकॉल को ध्यान में रखते हुए, आउटेज संभावना और थ्रूपुट के संदर्भ में प्रदर्शन का विश्लेषण किया जाता है। एनयू में वांछित लक्ष्य क्यूओएस सुनिश्चित करते समय एफयू का प्रदर्शन टीएस / पीएस पैरामीटर को इष्टतम रूप से चुनकर अधिकतम किया जाता है। ऊर्जा दक्षता में और सुधार के लिए, एक नई गतिशील बैटरी ऊर्जा (डीबीई) योजना प्रस्तावित की गई है जिसमें बैटरी ऊर्जा तैयार की गई ऊर्जा की मात्रा पर निर्भर करती है। यह प्रदर्शित किया जाता है कि बैटरी ऊर्जा का प्रबंधन करने के लिए डीबीई योजना का उपयोग करना एफबीई योजना के साथ संभव की तुलना में उच्च ऊर्जा दक्षता सुनिश्चित करता है।

वायरलेस सेंसर नेटवर्क (डब्ल्यूएसएन) और बॉडी एरिया नेटवर्क में, यह अक्सर वांछित होता है कि एक नोड अपने आसपास के क्षेत्र में अन्य नोड्स की सहायता करता है। इस तरह के नोड्स की बैटरी जीवनकाल और संचार सीमा काफी सीमित है। रिलेइंग नोड पर ईएच का उपयोग यह सुनिश्चित कर सकता है कि इसकी बैटरी जीवनकाल में काफी कमी नहीं आई है। कई व्यावहारिक प्रणालियों में, तात्कालिक सीएसआई का अनुमान उचित सटीकता के साथ लगाया जा सकता है। यह इस थीसिस में दिखाया गया है कि तात्कालिक सीएसआई की उपलब्धता आत्म-टिकाऊ ईएच उपकरणों को अपने बैटरी जीवन को बढ़ाने में काफी मदद कर सकती है। दो-हॉप एफडी रिले ढांचे में सीएसआई ज्ञान के प्रभाव की जांच करने के लिए, रिले में बुद्धिमान बैटरी प्रबंधन के साथ एक गतिशील टीएस प्रोटोकॉल प्रस्तावित है। स्थिर और सीएसआई निर्भर (गतिशील) टीएस ईएच प्रोटोकॉल का प्रदर्शन थ्रूपुट और औसत बैटरी ऊर्जा खपत के संदर्भ में विश्लेषण किया जाता है। गतिशील टीएस का उपयोग स्थिर टीएस योजना पर एफबीई और डीबीई ऊर्जा प्रबंधन योजनाओं दोनों के लिए पर्याप्त प्रदर्शन लाभ प्रदान करता है। इसके अलावा, टीएस ईएच पैरामीटर को इष्टतम रूप से चुनकर, डीबीई के साथ गतिशील टीएस रिले पर भारी बैटरी ऊर्जा बचत प्राप्त करता है।

संचार नेटवर्क में कम बिजली वाले उपकरणों में तेजी से वृद्धि को देखते हुए, इस थीसिस में विकसित अंतर्दृष्टि सिस्टम डिजाइनरों के लिए थ्रूपुट प्रदर्शन और बैटरी जीवनकाल के अनुकूलन के लिए काफी मूल्यवान हैं।

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ACRONYMS/ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
AF	Amplify-and-Forward
bpcu	Bits Per Channel Use
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CSI	Channel State Information
D2D	Device-to-Device
DBE	Dynamic Battery Energy
DC	Direct Current
DAC	Digital to Analog Converter
DF	Decode-and-Forward
DSP	Digital Signal Processing
EDGE	Enhanced Data GSM Evolution
EE	Energy Efficiency
EH	Energy Harvesting
eMTC	Enhanced Machine Type Communication
FBE	Fixed Battery Energy
FD	Full-Duplex
FDR	Full-Duplex Relay

FU	Far User
Gbps	Gigabits Per Second
GPRS	General Packet Radio Service
GSM	Global System for Mobiles
HD	Half-Duplex
HDR	Half-Duplex Relay
HPA	High Power Amplifier
HSPDA	High Speed Downlink Packet Access
HSPUA	High Speed Uplink Packet Access
HST	Harvest Store then Transmit
HT	Harvest then Transmit
IoT	Internet of things
ID	Information Decoding
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IT	Information Transmission
IR	Incremental Relaying
IRS	Intelligent Reflecting Surface
Kbps	Kilobits Per Second
L-EH	Linear Energy Harvesting
LNA	Low Noise Amplifier
LPWA	Low Powered Wide Area
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
Mbps	Megabits Per Second
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
mMTC	Massive Machine Type Communication
MRT	Maximal Ratio Transmission
MTC	Machine Type Communication
MTD	Machine Type Device
NDL	No Direct Link
NL-EH	Nonlinear Energy Harvesting

NOMA	Non-orthogonal Multiple Access
NU	Near User
OMA	Orthogonal Multiple Access
PDF	Probability Density Function
PS	Power Splitting
QoS	Quality of Service
RF	Radio Frequency
RSI	Residual Self Interference
SDFDL	Selective DF relaying with Direct Link
SE	Spectral Efficiency
SI	Self Interference
SIC	Successive Interference Cancellation
SINR	Signal to Interference plus Noise ratio
SNR	Signal to Noise ratio
SWIPT	Simultaneous Wireless Information and Power Transfer
TS	Time Switching
TWR	Two-Way Relay
WET	Wireless Energy Transfer
WiMax	Worldwide Interoperability for Microwave Access
WPT	Wireless Power Transfer

NOTATION

$\lvert\cdot\rvert$	Absolute value
$\lvert\lvert\mathbf{x}\rvert\rvert$	Euclidean norm of a vector $\mathbf{x}$
α	Time-switching parameter
ρ	Power-splitting parameter
$\mathbf{x}^H$	Hermitian (conjugate transpose) of vector $\mathbf{x}$.
$\mathcal{CN}(0,a)$	Zero mean complex Gaussian distribution with variance a
B	Bandwidth
D	Diversity order
E_{s}	Source transmit energy
E_{b}	Battery energy
E_{h}	Harvested energy
E_{in}	Available input energy at EH circuit
E_{sat}	Energy saturation threshold
$\exp[\,.\,]$	Exponential function
$E_n[\,.\,]$	Generalized exponential integral for real non-zero values of order n, where $E_n[x] = \int_1^\infty t^{-n} e^{-xt}\, dt$ $(n = 0,1,2,\ldots)$
$\mathbb{E}_X$	Expectation over random variables X
$\mathbb{E}_{X_1,X_2,\ldots,X_N}$	Expectation over random variables $X_1, X_2, \ldots, X_N$
f_{b}	Feedback bit
$f_X(x)$	Probability density function of random variable X
$F_X(x)$	Cumulative distribution function of random variable X
$F_X^{\mathrm{c}}(x)$	Complementary cumulative distribution function of random variable X
$\Gamma[\cdot]$	Gamma function defined on the complex plane except for 0 and, negative integers, $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t}\, dt$
$\gamma[\cdot,\cdot]$	Lower Incomplete Gamma function, where $\gamma[a,x] = \int_0^x t^{a-1} \exp(-t)\, dt$
$\Gamma[\cdot,\cdot]$	Upper Incomplete Gamma function, where $\Gamma[a,x] = \int_x^\infty t^{a-1} \exp(-t)\, dt$
$K_n[\cdot]$	n^{th} order modified Bessel's function of second kind, where $K_n[x] = \frac{1}{2}\left(\frac{x}{2}\right)^n \int_0^\infty t^{n-1} e^{-\frac{1}{t} - \left(\frac{x}{2}\right)^2 t}\, dt$
L	Number of far users
M	Number of source transmit antennas
$\max(.)$	Maximum
$\min(.)$	Minimum
ϕ	Path loss exponent
p_{f}	Far user outage probability

p_{n}	Near user outage probability
p_{o}	Outage probability
P_{s}	Source transmit power
R_{t}	Target rate
R_{s}	Symbol rate
σ^2	Noise variance
τ	Throughput
τ_{tr}	Target throughput
x_{f}	Transmit signal intended for far user
x_{n}	Transmit signal intended for near user
x_{s}	Transmit signal from the source
y_{n}	Received signal at the near user
y_{d}	Received signal at the destination
y_{f}	Received signal at the far user
y_{n}	Received signal at the near user
y_{r}	Received signal at the relay