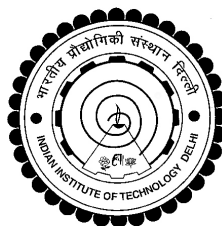


STRATEGIES FOR UNINTERRUPTED WIRELESS COMMUNICATION NETWORK WITH COOPERATIVE RF ENERGY HARVESTING NODES

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Indian Institute of Technology Delhi
August 2017**

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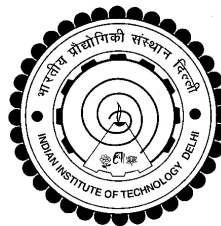
by

DEEPAK MISHRA

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Submitted

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



Indian Institute of Technology Delhi
August 2017

Certificate

This is to certify that the dissertation entitled **Strategies for Uninterrupted Wireless Communication Network with Cooperative RF Energy Harvesting Nodes**, submitted by **Mr. Deepak Mishra**, a Research Scholar, in the *Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, India*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under my supervision and guidance. The dissertation fulfills all requirements as per the regulations of this Institute and in my opinion has reached the standard needed for submission. Neither this dissertation nor any part of it has been submitted for any degree or academic award elsewhere.

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Acknowledgements

First of all, I would like to thank my supervisor Prof. Swades De for his guidance and encouragement which I received throughout my dissertation research journey. I am thankful to him for giving me the counsel and for painstakingly reading my reports. Without his invaluable advice and support it would not have been possible for me to complete this dissertation.

I take this opportunity to express my sincere thanks to Prof. Indra Narayan Kar, Prof. Shouri Chatterjee, and Prof. Kolin Paul for their valuable feedback during my end semester presentations. I would like to thank Prof. Kaushik R. Chowdhury, Prof. Wendi Heinzelman, Prof. Stefano Basagni, Prof. Soumya Jana, Dr. Dilip Krishnaswamy, and Dr. George C. Alexandropoulos for their valuable discussions and suggestions for improving my research work.

I would like to thank all my fellow researchers of the Computer Networks Research Group, who made this journey a memorable one. Further, I would like to extend them my best wishes for their future endeavors.

I would also like to thank Department of Science and Technology (DST) and P.G. Section of IIT Delhi for their International travel grant support for attending IEEE Consumer Communications and Networking Conference 2016 and IEEE International Conference on Communications 2016. Also, I would like to thank IBM Research India and Indo French Centre for Promotion of Advanced Research (IFCPAR/CEFIPRA) for granting me research fellowships to carry out my dissertation research.

I express my heartfelt thanks to my parents who have been a constant source of inspiration to me all along and their encouraging words made this endeavor possible. Finally, I would like to thank my family, friends, and all others whose names are not mentioned here but have helped me to accomplish this work.

Deepak Mishra

Abstract

Substantial benefits can be reaped with use of Wireless Sensor Networks (WSNs) technology in many applications. However, a wireless sensor node is energy constrained due to its limited battery size. Recently, radio frequency (RF) energy harvesting (EH) has emerged as a potential method for the proactive energy replenishment of wireless devices in Internet-of-Things (IoT). Unlike other EH techniques that depend on the environment, RF-EH can be predictable or on-demand, and as such it is better suited for supporting quality-of-service-based applications. However, RF-EH efficiency is scarce due to wireless propagation losses, low rectification efficiency and receiver sensitivity. Thus, this dissertation aims at enhancing the RF-EH efficiency by proposing innovative communications and systems level schemes by investigating cross-layer research areas like circuits and systems, wireless RF propagation, communication theory, and network protocols.

To analyze the practical efficacy of RF energy transfer (ET) technology, the first part of dissertation introduces a novel theoretical framework for analyzing RF charging behavior and deriving RF charging time distribution for a given residual voltage distribution. The analytical model is validated through hardware experiments and simulations. The proposed circuit model is then extended to characterize the renewable energy cycle in RF-EH sensor nodes by investigating the stored energy evolution for practical supercapacitor models. RF charging time and node lifetime expressions are derived for different supercapacitor models. Also, an experimentally verified novel duality principle is proposed to relate RF charging and sensor node's loading times. Further, using a generic simulation model for characterizing the complicated supercapacitor models, the effect of practical rechargeability constraints on sustainable network size is accurately investigated.

The second part presents experimental demonstration for the first time the proof-of-concept of novel "packetized" energy communication schemes, like multi-hop RFET, multi-path energy routing (MPER), and cooperative energy relaying that enable and enhance the usefulness of RF-EH communication networks. MPER helps improve RF-EH efficiency by first collecting the dispersed or dissipated RF energy transmitted by the RF source with the help of energy routers, and then directing it to the desired sensor node via paths other than the direct single hop path. To maximize the RF-ET efficiency in a two-hop scenario, a novel optimization model is proposed to determine the optimal relay placement (ORP) on a 2-D Euclidean plane. The tradeoff between energy scavenged and energy delivered to the target node is investigated and distributed energy beamforming

techniques are incorporated to enhance the end-to-end RF-ET efficiency. Simulation and experimental results illustrate that ORP provides significant energy saving over arbitrary relay positions. To further enhance the efficiency of multihop RF-ET, a novel no-impact to line-of-sight model for RP is proposed along with a piecewise linear approximation for harvested-received power characteristics to gain analytical insights on ORP.

Integration of ET and information transfer (IT) is a promising solution for realization of advanced self-sustainable architectures like wireless powered communication networks (WPCNs) and simultaneous wireless information and power transfer (SWIPT). However as the performance of WPCN and SWIPT is bottlenecked by low RF-ET efficiency, novel optimized RF-EH communication protocols are proposed in the third part to bridge the gap between ET and IT efficiency. Here first, the joint optimization of power allocation, relay placement, and power splitting ratio is carried out to minimize outage probability at RF-EH destination in relay-assisted SWIPT for both with and without availability of direct link. Generalized convexity of the outage minimization problem is proved and global-optimal solutions are obtained for the Rician fading channel. Next, a novel relay-powered cooperative RF-EH network model, called RPCN, is proposed to overcome the shortcomings of conventional WPCN. Closed-form expressions for outage probability and ergodic capacity are derived. Optimal time allocation for maximizing delay-constrained throughput in RPCN is also investigated. Lastly, a novel integrated information and energy relaying protocol is proposed to address the doubly-near-far problem in WPCN by efficiently utilizing the harvested energy of the relay for energy relaying or/and information relaying. Considering Rician fading, closed-form expressions are derived for the mean harvested power at EH information source and outage probability for decode-and-forward relaying with maximal-ratio-combining at hybrid access point (HAP). Analytical insights on optimal relaying mode along with global-optimal utilization of harvested energy at relay are also provided to fill the existing research gap.

In the last part, to address the needs of advanced RF-EH communications in IoT and 5G networks, a novel integrated information relay and energy supply model is presented. This proposal jointly optimizes the throughput performance of WPCN and SWIPT over Rician channels by efficiently allocating the time for ET and IT while effectively positioning the relay. Tight closed-form approximations for the global-optimal solutions are also derived. Finally, to maximize the sum-throughput in RF-powered device-to-device communications, a novel optimized HAP-controlled transmission protocol is proposed for the harvested energy-aware joint mode selection and time allocation for ET and IT.

सार

वायरलेस सेंसर नेटवर्क (डब्ल्यूएसएनएस) के उपयोग के साथ पर्याप्त लाभ काटा जा सकता है कई अनुप्रयोगों में प्रौद्योगिकी हालांकि, एक वायरलेस सेंसर नोड ऊर्जा विवश है इसकी सीमित बैटरी आकार के कारण हाल ही में, रेडियो आवृत्ति (आरएफ) ऊर्जा संचयन (ईएच) वायरलेस डिवाइसों की सक्रिय ऊर्जा पुनःपूर्ति के लिए संभावित विधि के रूप में उभरा इंटरनेट-ऑफ-थिंग्स (आईओटी) में पर्यावरण पर निर्भर अन्य ईएच तकनीकों के विपरीत, आरएफ-ईएच उम्मीद के मुताबिक या ऑन-डिमांड हो सकता है, और जैसे कि यह समर्थन करने के लिए बेहतर है गुणवत्ता-आधारित सेवा-आधारित अनुप्रयोग हालांकि, वायरलेस के कारण आरएफ-ईएफ दक्षता दुर्लभ है प्रचार घाटे, कम सुधार दक्षता और रिसीवर संवेदनशीलता इस प्रकार, यह शोध प्रबंध का उद्देश्य अभिनव संचारों को प्रस्तावित करके आरएफ-ईएच दक्षता में वृद्धि करना है और सर्किट जैसे पार-परत शोध क्षेत्रों की जांच कर सिस्टम स्तर की योजनाएं और सिस्टम, वायरलेस आरएफ प्रेरक, संचार सिद्धांत, और नेटवर्क प्रोटोकॉल।

आरएफ ऊर्जा हस्तांतरण (एटी) प्रौद्योगिकी की व्यावहारिक प्रभावकारिता का विश्लेषण करने के लिए, पहला भाग निबंध के आरएफ चार्ज करने के व्यवहार का विश्लेषण करने के लिए एक उपन्यास सैद्धांतिक रूपरेखा का परिचय और दिए गए अवशिष्ट वोल्टेज वितरण के लिए आरएफ चार्ज करने का समय वितरण। विश्लेषणात्मक मॉडल हार्डवेयर प्रयोगों और सिमुलेशन के माध्यम से मान्य है। प्रस्तावित सर्किट मॉडल को आरएफएच में नवीकरणीय ऊर्जा चक्र की विशेषता के लिए बढ़ा दिया गया है संवेदक नोड्स, जो कि व्यावहारिक सुपरकोएसिटर के लिए संग्रहीत ऊर्जा विकास की जांच कर रहा है मॉडल के। आरएफ चार्जिंग समय और नोड जीवन भर की अभिव्यक्तियां अलग-अलग सुपरकोएसिटर के लिए ली गई हैं मॉडल के। इसके अलावा, एक प्रयोगात्मक रूप से सत्यापित उपन्यास द्वैत सिद्धांत का प्रस्ताव है आरएफ चार्जिंग और सेंसर नोड के लदान समय से संबंधित है। इसके अलावा, एक सामान्य सिमुलेशन का उपयोग करना जटिल सुपर स्पेसिड मॉडलों की विशेषता के लिए मॉडल, व्यावहारिक का प्रभाव टिकाऊ नेटवर्क आकार पर रिचार्जबल की कमी सही जांच की जाती है।

दूसरा भाग प्रायोगिक अवधारणा के लिए पहली बार प्रायोगिक प्रदर्शन प्रस्तुत करता है उपन्यास "पैकेटिज्ड" ऊर्जा संचार योजनाएं, जैसे मल्टी-हॉप आरएफईटी, मल्टी-पाथ एनर्जी रूटिंग (एमपीएआर), और सहकारी ऊर्जा रिलेइंग जो सक्षम और बढ़ाते हैं आरएफ-ईएच संचार नेटवर्क की उपयोगिता एमपीए आरएफ-एच को बेहतर बनाने में मदद करता है पहले आरएफ द्वारा प्रेषित या फैलाने वाले आरएफ ऊर्जा को इकट्ठा करके दक्षता ऊर्जा राउटर की मदद से स्रोत, और उसके बाद वांछित सेंसर नोड को निर्देशित कर रहा है प्रत्यक्ष एकल हॉप पथ के अलावा अन्य मार्गों के माध्यम से आरएफ-एच दक्षता को अधिकतम करने के लिए दो-हॉप परिदृश्य, इष्टतम रिले को निर्धारित करने के लिए एक उपन्यास अनुकूलन मॉडल प्रस्तावित किया गया है 2 डी इयूक्लिडियन विमान पर प्लेसमेंट (ओआरपी) ऊर्जा के बीच का व्यवहार और विच्छेदित लक्ष्य नोड को दिया गया ऊर्जा जांच की जाती है और ऊर्जा बीमॉफॉर्मिंग वितरित करती है तकनीकों को एंड-टू-एंड आरएफ-एच दक्षता को बढ़ाने के लिए शामिल किया गया है। अनुकरण और

प्रायोगिक परिणाम बताते हैं कि ओआरपी मनमाना पर महत्वपूर्ण ऊर्जा बचत प्रदान करता है रिले पदों मल्टीहॉप आरएफ-ईटी की दक्षता को और बढ़ाने के लिए, एक उपन्यास नो-प्रभाव आरपी के लिए लाइन-ऑफ-विज़ुअल मॉडल के लिए प्रस्तावित किया जाता है, इसके लिए एक टुकड़ी के अनुसार रैखिक सन्निकटन ओआरपी पर विश्लेषणात्मक अंतर्दृष्टि हासिल करने के लिए कटाई-प्राप्त शक्ति विशेषताओं

ईटी और सूचना हस्तांतरण (आईटी) का एकीकरण, प्राप्ति के लिए एक आशाजनक समाधान है वायरलेस पावर संचार नेटवर्क जैसे उन्नत स्व-स्थायी आर्किटेक्चर (डब्ल्यूपीसीएन) और एक साथ वायरलेस सूचना और पावर ट्रांसफर (एसडब्ल्यूआईपीटी)। हालांकि डब्ल्यूपीसीएन और एसडब्ल्यूआईपीटी के प्रदर्शन को कम आरएफ-ईटी दक्षता से बाधा उत्पन्न होती है, उपन्यास अनुकूलित आरएफ-ईएच संचार प्रोटोकॉल का प्रस्ताव तीसरे भाग में है ईटी और आईटी दक्षता के बीच अंतर को पुल करने के लिए यहां सबसे पहले, संयुक्त अनुकूलन बिजली आवंटन, रिले प्लेसमेंट, और बिजली बंटवारे अनुपात को कम करने के लिए किया जाता है रिले-सहायता प्राप्त एसडब्ल्यूआईपीटी के साथ और बिना दोनों के आरएफ-ईएच गंतव्य पर आउट्रेज संभावना सीधी लिंक की उपलब्धता आउट्रेज न्यूनीकरण समस्या की सामान्यीकृत उत्तलता सिद्ध है और विश्व-इष्टतम समाधान रशियन लुप्त होती चैनल के लिए प्राप्त किए जाते हैं। आगामी, आरपीसीएन नामक एक उपन्यास रिले संचालित सहकारी आरएफ-एच नेटवर्क मॉडल को प्रस्तावित किया गया है परंपरागत डब्ल्यूपीसीएन की कमियों को दूर करना आउट्रेज के लिए बंद-प्रपत्र अभिव्यक्ति संभावना और एर्गोडिक क्षमता व्युत्पन्न होती है। अधिकतम करने के लिए इष्टतम समय आवंटन आरपीसीएन में देरी-बाधित थ्रूपुट की जांच भी की जाती है। अंत में, एक उपन्यास एकीकृत सूचना और ऊर्जा रिलेइंग प्रोटोकॉल को दोगुना-निकट-दूर तक समस्या से निपटने के लिए प्रस्तावित किया गया है ऊर्जा रिलेयरिंग के लिए रिले की कटाई ऊर्जा का कुशल उपयोग करके डब्ल्यूपीसीएन में या / और जानकारी प्रसारण रशियन लुप्त होती, बंद-रूप अभिव्यक्तियों को ध्यान में रखते हुए ईएच सूचना स्रोत और आउट्रेज संभावना पर मतलब कटाई की शक्ति के लिए प्राप्त होते हैं हाइब्रिड एक्सेस में अधिकतम-अनुपात-संयोजन के साथ डीकोड और फॉरवर्ड रिलेइंग के लिए बिंदु (एचएपी) वैश्विक इष्टतम के साथ इष्टतम रिलेइंग मोड पर विश्लेषणात्मक अंतर्दृष्टि मौजूदा शोध के अंतराल को भरने के लिए रिले में कटाई ऊर्जा का उपयोग भी किया जाता है।

आखिरी भाग में, आईओटी में उन्नत आरएफ-ईएच संचार की जरूरतों को पूरा करने के लिए और 5 जी नेटवर्क, एक उपन्यास एकीकृत सूचना रिले और ऊर्जा आपूर्ति मॉडल प्रस्तुत किया गया है। यह प्रस्ताव संयुक्त रूप से डब्ल्यूपीसीएन और एसडब्ल्यूआईपीटी के ओवरपुट प्रदर्शन का अनुकूलन करता है प्रभावी ढंग से पोजीशनिंग करते समय, ईटी और आईटी के लिए समय से प्रभावी ढंग से आवंटित करके रशियन चैनल रिले ग्लोबल-इष्टतम समाधान के लिए तंग बंद-रूप अनुमानित हैं भी व्युत्पन्न अंत में, आरएफ द्वारा संचालित डिवाइस-टू-डिवाइस में सम-थ्रूपुट को अधिकतम करने के लिए संचार, एक उपन्यास अनुकूलित एचएपी-नियंत्रित ट्रांसमिशन प्रोटोकॉल प्रस्तावित है कटाई ऊर्जा-जागरूक संयुक्त मोड चयन और ईटी और आईटी के लिए समय आवंटन

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List of Acronyms

AF	Amplify-and-Forward
AP	Access Points
AWGN	Additive White Gaussian Noise
BB	Branch and Bound
CCDF	Complimentary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CGM	Conjugate Gradient Method
CMP	Constraint Minimization Problem
CPL	Constant Power Loading
CSC	Complementary Slackness Conditions
CSI	Channel State Information
DC	Direct Current
DE	Differential Equation
DET	Direct Energy Transfer
DF	Decode-and-Forward
D2D	Device-to-Device
EH	Energy Harvesting
EIRP	Effective Isotropic Radiated Power
ER	Energy Relaying
ET	Energy Transfer
ESR	Equivalent Series Resistance
EVB	Evaluation Board

E2E	End-to-End
GS	Golden Section
HAP	Hybrid Access Point
HRP	Harvested-Received Power
HTE	Harvest-then-Transfer Energy
IC	Integrated Circuit
iDEM	Integrated Data and Energy Mule
IT	Information Transfer
IoT	Internet-of-Things
IR	Information Relaying
ISM	Industrial, Scientific and Medical
i ² ER	Integrated Information and Energy Relaying
i ² RES	Integrated Information Relaying and Energy Supply
KKT	Karush-Kuhn-Tucker
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
LoS	Line-of-Sight
LTE	Long-Term Evolution
MGF	Moment Generating Function
MHET	Multi-Hop RF Energy Transfer
MIMO	Multiple-Input-Multiple-Output
MPER	Multi-Path Energy Routing
MRC	Maximal Ratio Combining
MS	Mode Selection
M2M	Machine-to-Machine
NCF	Near Convex Function
Ni-LoS	No-Impact on Line-of-Sight
PWLA	Piecewise Linear Approximation
ORP	Optimal Relay Placement
OFDMA	Orthogonal Frequency Division Multiple Access
OTA	Optimal Time Allocation
PA	Power Allocation
PB	Power Beacons
PDF	Probability Density Function
PR	Polak-Ribiere

PS	Power Splitting
QoS	Quality of Service
REC	Renewable Energy Cycle
RF	Radio Frequency
RMSE	Root Mean Square Error
RP	Relay Placement
RPCN	Relay-Powered Cooperative Network
SNR	Signal-to-Noise-Ratio
SWIPT	Simultaneous Wireless Information and Power Transfer
TA	Time Allocation
TMP	Throughput Maximization Problem
TS	Time Switching
UMP	Utility Maximization Problem
WIT	Wireless Information Transfer
WPCNs	Wireless Powered Communication Networks
WSNs	Wireless Sensor Networks
2HET	Two-Hop RF Energy Transfer

List of Symbols

P	Charging power
I	Charging current
V	Charging voltage
V_C	Voltage across capacitor
V_R	Voltage across resistor
V'	Residual voltage
C	Capacitance
Q	Charge stored in capacitor
R	Resistance
P_{cons}^{avg}	Average power consumption
I_{cons}^{avg}	Average current consumption
T_C	Charging time
T_L	Loading time
V_0	Supply voltage
D_C	Duty cycle
t_o	Time spent during communication and radio transition operations
I_o	Current consumption during communication and radio transition operations
$I_{se}, I_w, \text{ and } I_{sl}$	Current consumption during sensing, data logging, and sleep states
$N_{s/n}$	Number of sensors per node
$t_r \text{ and } t_w$	Sensor response time and data logging time
t_d	Day duration
V_H, V_L	High and low voltage levels
E	Energy level

F_n and f_n	CDF and PDF for normal distribution
q and t	Dummy variables for charge and time
F	Cumulative Distribution Function
f	Probability Density Function
T	Transmission block duration
h_{ij}	Channel gain between node i and j
a_{ij}	Antenna systems related gain between node i and j
l	Path loss exponent
n_i	Received noise signal at node i
σ^2	Noise variance
P_t	Transmit power
p_{out}	Outage probability
R_0	Information rate
$\mathcal{E}_C$	Ergodic capacity
$\mathcal{L}$	Lagrangian function
$v, v_0, v_1, v_2, \nu, \nu_1, \nu_2$	Lagrange multipliers
ρ, α	TS or PS parameters
τ	Throughput
ε	Eccentricity of ellipse
ϵ, ξ	Tolerances
η	RF-to-DC rectification efficiency
P_{t_i}	Transmit power of node i
P_0	Transmit power of HAP
N	Total number of nodes
P_T	Total transmit power budget
D	End-to-end distance between source and destination
d_{ij}	Distance between node i and j
λ	Wavelength
H_i	Channel gain between HAP and node i
(x_i, y_i)	x and y coordinates for node i and j
$\Pr$	Probability
K	Rice factor
γ	Signal-to-noise-ratio
$\mathbb{L}(\cdot)$	PWLA function
$W_k(\cdot)$	Lambert function with $k = 0, -1$

$\mathcal{S}$	Source
$\mathcal{R}$	Relay
$\mathcal{D}$	Destination
L_a	Largest dimension of antenna
L	Largest dimension of the field
T_{ON} and T_{OFF}	ON and OFF times for RF-ET
$Q_{(\cdot)}(\cdot, \cdot)$	Generalized Marcum Q-function
$\mathbb{E}$	Expectation operator
$\overline{F}$	Complimentary Cumulative Distribution Function
d_F	Fraunhoffer distance
ζ_P	Harvested power threshold
ζ_I	Information outage threshold
$\mathbf{K}_m$	Modified Bessel function of second kind and order m.
$\mathbf{I}_m$	Modified Bessel function of first kind and order m.
θ	Fraction of harvested energy available for information transfer
$P_{\text{con}}^{\text{tx}}$	Static power consumption
$\hat{\sigma}$	Radar cross section or echo area
P_r	Received RF power
P_h	Harvested DC power
m	Mode selection variable
$\mathcal{M}$ and $\mathcal{C}$	Slope and Intercept of the PWLA function