

Novel Strategies for Lifetime Enhancement of Energy Harvesting Sensor Nodes

A Thesis submitted by
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in partial fulfillment of the requirements for the award of the degree of
Doctor of Philosophy



॥ त्वं ज्ञानमयो विज्ञानमयोऽसि ॥

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Declaration

I hereby declare that the work presented in this thesis titled *Novel Strategies for Lifetime Enhancement of Energy Harvesting Sensor Nodes* submitted to the Indian Institute of Technology Jodhpur in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Dr. Arun Kumar Singh and Dr. Satyajit Sahu. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to any other Institute or University in India or abroad for the award of any degree or diploma.



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Certificate

This is to certify that the thesis titled *Novel Strategies for Lifetime Enhancement of Energy Harvesting Sensor Nodes*, submitted by *Arpita Jaitawat (P15EE002)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by her under our supervision. To the best of our knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



Satyajit Sahu

Arun Kumar Singh and Satyajit Sahu
Ph.D. Thesis Supervisors

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List of Symbols

<i>Symbol</i>	<i>Description</i>
$E_k^{total,B}$	Total energy available for transmission when battery is the ESD
$E_k^{total,SC}$	Total energy available for transmission when supercapacitor is the ESD
N_0	Noise variance
N_{DP}	Step size for optimal DP
N_{UP}	Total number of thresholds
N_s	Total number of symbols
\cdot_+	Rectifier function which gives the positive part of the argument
T	Total transmission time
K	Total number of epoch/transmission blocks
E_k	Energy harvested at k^{th} time instance
E_k^S	Energy state of energy buffer at k^{th} time instance
E_{max}^B	Maximum storage capacity of a battery
E_{max}^{SC}	Maximum storage capacity of a supercapacitor
E_{max}	Maximum storage capacity of an energy buffer
$E_k^{B,T}$	Energy transmitted at k^{th} time instance when battery is the ESD
$E_k^{SC,T}$	Energy transmitted at k^{th} time instance when supercapacitor is the ESD
E_k^T	Energy transmitted at k^{th} time instance
Z_k	Sensing and processing cost of sensor node at k^{th} time instance
ϵ_B	Battery self-discharge rate
ϵ_{SC}	Supercapacitor self-discharge rate
η_B	Storage efficiency of the battery
η_{SC}	Storage efficiency of the supercapacitor
η	Storage efficiency of the energy buffer
$\rho_{leakage}^B$	Energy loss due to battery self-discharge
$\rho_{leakage}^{SC}$	Energy loss due to supercapacitor self-discharge
$\rho_{leakage}$	Energy loss due to energy buffer self-discharge
\mathbb{CN}	Circularly symmetric complex normal distribution
$E_0^{s,B}$	Initial energy state of the battery
$E_k^{s,B}$	Battery energy state at k^{th} transmission block
$E_0^{s,SC}$	Initial energy state of the supercapacitor
$E_k^{s,SC}$	Supercapacitor energy state at k^{th} transmission block
$\mathbb{E}[\cdot]$	Mathematical expectation
$\lfloor \cdot \rfloor$	floor function
γ_k	Channel SNR
h_k	Channel fading coefficient
\mathbb{R}^+	Positive real numbers
$[D_k^{SC}]^+$	Rectifier function for different modes of supercapacitor
$[D_k^B]^+$	Rectifier function for different modes of battery
σ^2	Channel Variance
$\sum_{j=1}^k$	Summation from $j=1$ to $j=K$
t_{bc}	Transmission block length

Symbol	Description
t_k	k^{th} time instance
$unif$	Uniformly distributed random variable
$x_k(i)$	i^{th} symbol transmitted in the k^{th} transmission block from N_s symbols
$y_k(i)$	i^{th} symbol received in the k^{th} transmission block from N_s symbols

List of Abbreviations

<i>Abbreviation</i>	<i>Full form</i>
ADC	Analog to digital converter
AM	Amplitude Modulation
ASIC	Application-specific integrated circuit
CSI	Channel State Information
DP	Dynamic Programming
EDLC	Electric Double Layer Capacitor
EE	Energy Efficiency
EH	Energy Harvesting
EM	Electromagnetic Radiation
ESD	Energy Storage Device
ESI	Energy State Information
FM	Frequency Modulation
FPGA	Field Programmable Gate Arrays
GPS	Global Position System
HSU	Harvest-Store-Use
HU	Harvest-Use
HUS	Harvest-Use-Store
HW	Hardware
i.i.d.	Independent and Identically Distributed
IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Internet Protocol
KKT	Karush-Kuhn-Tucker
Li-ion	Lithium ion
LPWA	Low-Power Wide-Area
M2M	Machine-to-Machine
MDP	Markov Decision Process
NFC	Near Field Communication
NL	Network Lifetime
OBU	On board Unit

<i>Abbreviation</i>	<i>Full form</i>
RF	Radio Frequency
RFID	Radio Frequency Identification
Rx	Receiver
SC	Supercapacitor
SNR	Signal-to-noise ratio
SoC	State of Charge
SW	Software
Tx	Transmitter
WPT	Wireless Power Transfer
WSN	Wireless Sensor Network