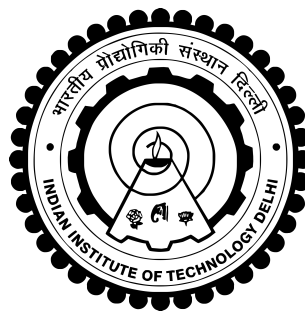


DESIGN AND OPTIMIZATIONS TOWARD SMART GRID CONNECTED GREEN FUTURE COMMUNICATION NETWORKS

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JULY 2024**

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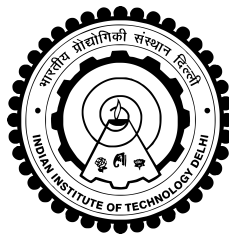
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Department of Electrical Engineering

submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

**To my parents,
Mrs. Uma Balakrishnan
and
Late Mr. Dandapani Balakrishnan**

Certificate

This is to certify that the dissertation entitled **Design and Optimizations Toward Smart Grid Connected Green Future Communication Networks**, submitted by **Mr. Ashutosh Balakrishnan**, a Research Scholar, in the *Department of Electrical Engineering, under IIT Delhi–NYCU Taiwan, Joint Doctoral Program, Indian Institute of Technology Delhi, New Delhi, India*, for the award of the joint degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under our supervision and guidance. The dissertation fulfills all requirements as per the regulations of this Institute and in our 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 and foremost, I would like to express my deep and sincere gratitude to my advisor, Prof. Swades De, without whose guidance this dissertation would not have fructified. I thank him for encouraging me, when I joined under him as an intern, and motivating me to pursue a Ph.D. I thank him for shaping my thought process, believing in me, and giving me confidence due which we could solve and publish research problems, which are part of this dissertation. It would not be an overstatement, but his enormous support, critical analysis, endless research discussions, and invaluable guidance during my Ph.D., is a primary reason behind this research work. I am also extremely thankful to him for presenting me with an opportunity to enroll in joint collaborative Ph.D. program with NYCU, Taiwan. I feel incredibly privileged to be his student and thank him for his tutelage.

Next, I express heartfelt gratitude towards my co-advisor Prof. Li-Chun Wang. I thank him for providing me insightful advice which helped to mature my research and significantly improve my presentation skills. I thank him for hosting me at NYCU Taiwan and providing me access to all research facilities in IoT Lab, NYCU. I would then like to thank my IITD and NYCU research committee members, Prof. Shouri Chatterjee, Prof. B. S. Panda, Prof. Arpan Chattopadhyay, Prof. Kai-Ten Feng, Prof. Chun-Hung Liu, Prof. Yu-Jia Chen, and Prof. Meng-Lin Ku. Their valuable suggestions have significantly improved the quality of my dissertation.

I am grateful to Dr. Nancy Varshney, Mr. Sumit Singh, Dr. Sushmita Ghosh, Ms. Payali Das and Mr. Abhilash Gaur for their invaluable emotional support and camaraderie. I express gratitude to Biswajit, Pialy, Isha, Anjali, Aakash, and Siddharth for the wonderful memories. I thank my seniors, Dr. Vini Gupta, Dr. Anshul Thakur, and Dr. Suraj Suman for their timely guidance. Grateful to the wonderful lab-mates at the Communication Networks Research Group (CNRG) for the fun and research discussions. Grateful to Dr. Shubhankar Majumdar for his support since B.Tech.

I thank the Ministry of Education, Govt. of India, for providing scholarship and contingency support through the Prime Minister's Research Fellowship program. I thank Ministry of Science and Technology (MOST), Taiwan, and IEEE Communication Soci-

ety (ComSoc) for providing me travel grant, enabling me to participate in IEEE Global Communications Conference (GLOBECOM), 2022 and IEEE International Conference on Communications (ICC), 2024. I express my gratitude to Dr. Sheba Shadrach for her help in getting administrative approvals.

I would like to thank my grand parents, Mrs. Parvathy Rangan and Mr. Sirugamani Vaidyanathan Rangan, for being a source of inspiration and motivation for the future generations to look up to. Their contribution to our lives cannot be justified with words. I thank them for instilling upright values since childhood and for their unconditional support to my mother at the times of distress. I thank my aunt Ms. Usha Rangan for being with my mother in the thick and thin. I am grateful to Mrs. Vidhya Nityanand, Mr. B. Nityanand, and Krithika for their help and support. I would like to thank my mother, Mrs. Uma Balakrishnan. It is rightly said that, “*naasti mātṛsamā guru, naasti mātṛsamā puṇyaha, naasti mātṛḥ samah sakhā*”, meaning that no one can be more honorable than ones mother, as she is the best teacher and friend. I thank her for all her teachings, which have and shall continue to guide me in various aspects of life. A special mention to our pet *icy*, who has been an inseparable part of this journey.

Lastly, I thank the almighty, for his generosity and blessings, without which this dissertation could not have become a reality.



Ashutosh Balakrishnan

Abstract

Green networking solution is a major theme in the upcoming 6G communications. The rising proliferation of the Internet of Things alongside evolving communication technology towards sixth generation (6G) communication networks is estimated to significantly increase the quality of service (QoS) requirements of the network devices. 6G communications based technologies like autonomous vehicles, metaverse, virtual reality, and ultra reliable low latency use cases are expected to enhance the user quality of experience (QoE). To meet the rising QoS/QoE requirements, mobile network operators are expected to densify the deployment of base stations (BSs) in the network, resulting in a potential rise in network energy consumption and thereby carbon footprint. In addition to mitigating network carbon footprint generation, cost incurred to the mobile network operator in network deployment and operations also requires to be considered while network designing, so as to realize scalable networks. The main objective through this dissertation, is to design energy efficient and cost optimal, self-sustainable scalable future networks.

To realize energy and cost-efficient networks, the BSs are provisioned with renewable energy power supply in addition to the traditional power grid connectivity. With the BSs being spatially distributed in a geographical area, designing grid connected and energy harvesting powered networks is challenging due to the stochastic variation of green energy harvest and BS load, leading to Spatio-temporal traffic-energy imbalances across the network. By modelling the degree of skewness of these imbalances, the first topic of dissertation presents a cooperative coverage adjustment based analytical framework to mitigate the effect of these imbalances on user QoS and operator revenue. Considering the network traffic profile to be heterogeneous, i.e., have delay-constrained as well as delay-tolerant traffic, a tractable lower bound on the rate requirement of a user is derived in this work as a function of QoS parameters defined by 3GPP. The revenue earned by the network operator is mathematically formulated and is observed to be a non-deterministic polynomial-time (NP) hard problem, with the revenue function depending on the number of users in the network and green energy allocated. The optimization problem is algorithmically solved for both these decision variables.

The second topic of the dissertation presents an analytical study wherein the power grid infrastructure is leveraged through cooperative energy transfer, by exploiting the traffic-energy imbalances, to improve the temporal network energy utilization without compromising the user QoS. The cooperative energy transfer framework is designed and

optimized independently from two diverging objectives, carbon footprint minimization and operator revenue maximization. The problems are reformulated as convex optimization problem and optimal values are derived. As a carbon-free mode of network operation, “energy-producer” mode of network operation is proposed wherein the BSs act as distributed energy sources to the power grid, realizing a self-sustainable communication network. From the operator perspective, “energy-prosumer” mode of operation involving flexibility of energy purchase from the grid in addition to energy selling and transfer is proposed. The proposed strategies are evaluated and compared with the state-of-art.

The third part of the dissertation extends the cooperative energy transfer framework and studies the prospect of designing self sustainable and self-organizing BS clusters from an energy perspective. The study first analyses a standalone grid connected and solar powered BS system by modelling the BS green energy storage as a three state discrete time Markov chain (DTMC). This work studies the computational overhead required in a grid connected and solar powered communication system to compute the energy outage, and compares the existing literature with the proposed DTMC based framework. For a multi-BS framework, a computationally efficient distributed energy bank based energy cooperation strategy is proposed, wherein the system of BSs is modelled as a two state DTMC. The capital expenditure is optimized by jointly optimizing the solar provisioning in addition to the BS cluster size, towards attaining self-sustainability.

The fourth part of the thesis involves a joint traffic-energy management in grid connected and solar powered system. The study motivates the need for a joint analysis, thereby improving the user QoS in addition to improving the network green energy utilization. Taking the system constraints into consideration, the proposed cooperative coverage adjustment and sharing of energy (CASE) framework is proposed. The CASE framework is mathematically simulated and compared with the competitive state-of-art. The proposed joint CASE framework provides superior network QoS and operator profit gains over the state of art, in addition to realizing self-sustainable BS clusters at a much reduced CAPEX.

The final part of the thesis explores the possibility of integrating the existing grid connected and solar powered terrestrial networks with aerial communication technologies. Specifically, through the dissertation, a High Altitude Platform Station (HAPS) aided and power grid connected communication framework is explored. The proposed framework aims offload excess users with the solar powered terrestrial macro base station (tMBS) to the HAPS mounted MBS (hMBS) in the event of high traffic or low energy harvest.

The solar powered tMBS utilizes the power grid connectivity purely for energy selling rather than energy procurement. The inherent communication and energy networks in the proposed system are studied and modelled jointly as a six state DTMC. The paper also provides analytical bounds on the solar provisioning required at the hMBS for radio access network functions. The proposed framework is compared with a without offloading and grid energy procurement based competitive state of art, in terms of network QoS and annual operator profit. Our simulation based performance studies demonstrate that the proposed framework under limited hMBS offloading capability offers gains compared to the competitive state of the art, up to 21% enhanced network QoS and 64% increased operator profit.

The communication network frameworks discussed in the dissertation are expected to realize energy sustainable and cost-profitable networks, incentivizing the telecommunication service providers to move towards green future networks.

Keywords: Networked energy systems, energy sustainability, smart grid networks, green communication, techno-economic analysis

सार

आगामी 6G संचार में ग्रीन नेटवर्किंग समाधान एक प्रमुख विषय है। छठी पीढ़ी (6G) संचार नेटवर्क की ओर विकसित संचार प्रौद्योगिकी के साथ-साथ इंटरनेट ऑफ थिंग्स के बढ़ते प्रसार से नेटवर्क उपकरणों की सेवा की गुणवत्ता (QoS) आवश्यकताओं में उल्लेखनीय वृद्धि होने का अनुमान है। स्वायत्त वाहन, मेटावर्स, वर्चुअल रियलिटी और अल्ट्रा विश्वसनीय कम विलंबता उपयोग मामलों जैसी 6G संचार आधारित प्रौद्योगिकियों से उपयोगकर्ता के अनुभव की गुणवत्ता (QoE) में वृद्धि होने की उम्मीद है। बढ़ती QoS/QoE आवश्यकताओं को पूरा करने के लिए, मोबाइल नेटवर्क ऑपरेटरों से नेटवर्क में बेस स्टेशनों (BS) की तैनाती को घटाने की उम्मीद है, जिसके परिणामस्वरूप नेटवर्क ऊर्जा खपत और इस प्रकार कार्बन फुटप्रिंट में संभावित वृद्धि हो सकती है। नेटवर्क कार्बन फुटप्रिंट उत्पादन को कम करने के अलावा, नेटवर्क परिनियोजन और संचालन में मोबाइल नेटवर्क ऑपरेटर को होने वाली लागत पर भी नेटवर्क डिजाइनिंग के दौरान विचार करने की आवश्यकता है, ताकि स्केलेबल नेटवर्क का एहसास हो सके। इस शोध प्रबंध के माध्यम से मुख्य उद्देश्य ऊर्जा कुशल और लागत इष्टतम, स्व-स्थायी स्केलेबल भविष्य के नेटवर्क को डिजाइन करना है।

ऊर्जा और लागत-कुशल नेटवर्कों को साकार करने के लिए, बीएस को पारंपरिक पावर ग्रिड कनेक्टिविटी के अलावा अक्षय ऊर्जा बिजली आपूर्ति का प्रावधान किया गया है। बीएस के भौगोलिक क्षेत्र में स्थानिक रूप से वितरित होने के कारण, ग्रिड से जुड़े और ऊर्जा संचयन संचालित नेटवर्कों को डिजाइन करना चुनौतीपूर्ण है, क्योंकि हरित ऊर्जा संचयन और बीएस लोड में स्टोकेस्टिक भिन्नता होती है, जिससे पूरे नेटवर्क में स्थानिक-अस्थायी यातायात-ऊर्जा असंतुलन होता है। इन असंतुलनों की विषमता की डिग्री का मॉडलिंग करके, शोध प्रबंध का पहला विषय उपयोगकर्ता की गुणवत्ता सेवा और ऑपरेटर के राजस्व पर इन असंतुलनों के प्रभाव को कम करने के लिए एक सहकारी कवरेज समायोजन आधारित विश्लेषणात्मक ढांचा प्रस्तुत करता है। नेटवर्क ट्रैफिक प्रोफ़ाइल को विषम मानते हुए, यानी, देरी-बाधित और साथ ही देरी-सहिष्णु ट्रैफिक होने पर, इस कार्य में 3GPP द्वारा परिभाषित गुणवत्ता सेवा मापदंडों के एक फ़ंक्शन के रूप में उपयोगकर्ता की दर आवश्यकता पर एक सुगम निचली सीमा प्राप्त की गई है। नेटवर्क ऑपरेटर द्वारा अर्जित राजस्व को गणितीय रूप से तैयार किया जाता है और इसे एक गैर-निर्धारक बहुपद-समय (एनपी) कठिन समस्या के रूप में देखा जाता है, जिसमें राजस्व फ़ंक्शन नेटवर्क में उपयोगकर्ताओं की संख्या और आवंटित हरित ऊर्जा पर निर्भर करता है। इन दोनों निर्णय चरों के लिए अनुकूलन समस्या को एल्गोरिदम द्वारा हल किया जाता है।

शोध प्रबंध का दूसरा विषय एक विश्लेषणात्मक अध्ययन प्रस्तुत करता है जिसमें उपयोगकर्ता की गुणवत्ता से समझौता किए बिना अस्थायी नेटवर्क ऊर्जा उपयोग में सुधार करने के लिए, यातायात-ऊर्जा असंतुलन का फायदा उठाकर सहकारी ऊर्जा हस्तांतरण के माध्यम से पावर ग्रिड अवसंरचना का लाभ उठाया जाता है। सहकारी ऊर्जा हस्तांतरण ढांचे को दो अलग-अलग उद्देश्यों, कार्बन पदचिह्न न्यूनीकरण और ऑपरेटर राजस्व अधिकतमीकरण से स्वतंत्र रूप से डिजाइन और अनुकूलित किया गया है। समस्याओं को उत्तल अनुकूलन समस्या के रूप में सुधारा जाता है और इष्टतम मान निकाले जाते हैं। नेटवर्क संचालन के कार्बन-मुक्त मोड के रूप में, नेटवर्क संचालन का "ऊर्जा-उत्पादक" मोड प्रस्तावित किया गया है जिसमें बीएस पावर ग्रिड के लिए वितरित ऊर्जा स्रोतों के रूप में कार्य करते हैं, जिससे एक आत्मनिर्भर संचार नेटवर्क का एहसास होता है। ऑपरेटर के दृष्टिकोण से, ऊर्जा बिक्री और हस्तांतरण के अलावा ग्रिड से ऊर्जा खरीद की लचीलेपन को शामिल करते हुए संचालन का "ऊर्जा-उपभोक्ता" मोड प्रस्तावित किया गया है। प्रस्तावित रणनीतियों का मूल्यांकन किया जाता है और अत्याधुनिक के साथ तुलना की जाती है।

शोध प्रबंध का तीसरा भाग सहकारी ऊर्जा हस्तांतरण ढांचे का विस्तार करता है और ऊर्जा के दृष्टिकोण से आत्मनिर्भर और स्व-संगठित बीएस क्लस्टरों को डिजाइन करने की संभावना का अध्ययन करता है। अध्ययन में सबसे पहले बीएस ग्रीन एनर्जी स्टोरेज को तीन राज्य असतत समय मार्कोव श्रृंखला (DTMC) के रूप में मॉडलिंग करके एक स्टैंडअलोन ग्रिड से जुड़े और सौर ऊर्जा संचालित बीएस सिस्टम का विश्लेषण किया गया है। यह कार्य ऊर्जा आउटपुट की गणना करने के लिए ग्रिड से जुड़े और सौर ऊर्जा संचालित संचार प्रणाली में आवश्यक

कम्प्यूटेशनल ओवरहेड का अध्ययन करता है, और प्रस्तावित DTMC आधारित ढांचे के साथ मौजूदा साहित्य की तुलना करता है। एक बहु-बीएस ढांचे के लिए, एक कम्प्यूटेशनली कुशल वितरित ऊर्जा बैंक आधारित ऊर्जा सहयोग रणनीति प्रस्तावित की गई है, जिसमें बीएस की प्रणाली को दो राज्य DTMC के रूप में मॉडल किया गया है। आत्मनिर्भरता प्राप्त करने की दिशा में बीएस क्लस्टर आकार के अलावा सौर प्रावधान को संयुक्त रूप से अनुकूलित करके पूंजीगत व्यय को अनुकूलित किया जाता है।

थीसिस के चौथे भाग में ग्रिड से जुड़े और सौर ऊर्जा संचालित सिस्टम में संयुक्त ट्रेफ़िक-ऊर्जा प्रबंधन शामिल है। अध्ययन संयुक्त विश्लेषण की आवश्यकता को प्रेरित करता है, जिससे नेटवर्क हरित ऊर्जा उपयोग में सुधार के अलावा उपयोगकर्ता QoS में सुधार होता है। सिस्टम बाधाओं को ध्यान में रखते हुए, प्रस्तावित सहकारी कवरेज समायोजन और ऊर्जा का बंटवारा (CASE) ढांचा प्रस्तावित है। CASE ढांचे को गणितीय रूप से अनुकरण किया जाता है और प्रतिस्पर्धी अत्याधुनिक के साथ तुलना की जाती है। प्रस्तावित संयुक्त CASE ढांचा अत्याधुनिक नेटवर्क QoS और ऑपरेटर लाभ लाभ प्रदान करता है, साथ ही बहुत कम CAPEX पर आत्मनिर्भर BS क्लस्टर को साकार करता है।

थीसिस का अंतिम भाग मौजूदा ग्रिड से जुड़े और सौर ऊर्जा से चलने वाले स्थलीय नेटवर्क को हवाई संचार प्रौद्योगिकियों के साथ एकीकृत करने की संभावना का पता लगाता है। विशेष रूप से, शोध प्रबंध के माध्यम से, एक उच्च ऊंचाई वाले प्लेटफ़ॉर्म स्टेशन (HAPS) से सहायता प्राप्त और पावर ग्रिड से जुड़े संचार ढांचे का पता लगाया गया है। प्रस्तावित ढांचे का उद्देश्य उच्च ट्रेफ़िक या कम ऊर्जा उत्पादन की स्थिति में सौर ऊर्जा से चलने वाले स्थलीय मैक्रो बेस स्टेशन (tMBS) के साथ अतिरिक्त उपयोगकर्ताओं को HAPS माउंटेड MBS (hMBS) पर उतारना है। सौर ऊर्जा से चलने वाला tMBS पावर ग्रिड कनेक्टिविटी का उपयोग ऊर्जा खरीद के बजाय पूरी तरह से ऊर्जा बेचने के लिए करता है। प्रस्तावित प्रणाली में निहित संचार और ऊर्जा नेटवर्क का अध्ययन किया जाता है और छह राज्य DTMC के रूप में संयुक्त रूप से मॉडल बनाया जाता है। यह शोध पत्र रेडियो एक्सेस नेटवर्क कार्यों के लिए hMBS पर आवश्यक सौर प्रावधान पर विश्लेषणात्मक सीमाएँ भी प्रदान करता है। प्रस्तावित ढांचे की तुलना नेटवर्क QoS और वार्षिक ऑपरेटर लाभ के संदर्भ में ऑफ़लोडिंग और ग्रिड ऊर्जा खरीद आधारित प्रतिस्पर्धी अत्याधुनिक तकनीक से की जाती है। हमारे सिमुलेशन आधारित प्रदर्शन अध्ययन दर्शाते हैं कि सीमित एचएमबीएस ऑफ़लोडिंग क्षमता के अंतर्गत प्रस्तावित ढांचा, अत्याधुनिक प्रतिस्पर्धी तकनीक की तुलना में 21% तक उन्नत नेटवर्क क्यूओएस और 64% तक ऑपरेटर लाभ में वृद्धि प्रदान करता है।

शोध प्रबंध में जिन संचार नेटवर्क रूपरेखाओं पर चर्चा की गई है, उनसे ऊर्जा टिकाऊ और लागत-लाभदायक नेटवर्कों को साकार करने की उम्मीद है, जिससे दूरसंचार सेवा प्रदाताओं को हरित भविष्य नेटवर्क की ओर बढ़ने के लिए प्रोत्साहन मिलेगा।

कीवर्ड: नेटवर्क ऊर्जा प्रणालियाँ, ऊर्जा स्थिरता, स्मार्ट ग्रिड नेटवर्क, हरित संचार, तकनीकी-आर्थिक विश्लेषण

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List of Abbreviations

ICT	Information and Communication Sector
6G	Sixth generation
5G	Fifth generation
uRLLC	ultra Reliable and Low Latency Communication
mMTC	massive Machine Type Communication
eMBB	enhanced Mobile Broadband
QoS	Quality of Service
QoE	Quality of Experience
RAN	Radio Access Network
BS(s)	Base Station(s)
IoT	Internet of Things
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
MDP	Markov Decision Process
DTMC	Discrete Time Markov Chain
CASE	Coverage adjustment and Sharing of Energy
UAV	Unmanned aerial vehicle
HAPS	High Altitude Platform Station
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
GEO	Geostationary Earth Orbit
CCA	Cooperative Coverage Adjustment
PDF	Probability Density Function
EC	Energy Cooperation
hMBS	HAPS mounted Macro Base Station
3GPP	The 3rd Generation Partnership Project

tMBS	terrestrial Macro Base Station
PV	Photo Voltaic
OEMC	Operations and Energy Management Center
FCC	Federal Communications Commission
RNC	Radio Network Controller
MAC	Medium Access Control
NP	Non-deterministic Polynomial-time
WCA	Without Coverage Adjustment
PPP	Poisson Point Process
DC	Delay Constrained
DT	Delay Tolerant
PS	Packet Scheduler
CSI	Channel State Information
PLER	Packet Loss Error Rate
LTE	Long Term Evolution
OFDM	Orthogonal Frequency Division Multiplexing
TTI	Transmission Time Interval
SINR	Signal Interference to Noise Ratio
AWGN	Additive White Gaussian Noise
PSD	Power Spectral Density
CDF	Cumulative Distribution Function
RMSE	Root Mean Squared Error
UE	User Equipments
CO ₂	Carbon dioxide
WEC	Without Energy Cooperation
CA	Coverage Adjustment
SE	Sharing of Energy
LoS	Line of Sight
nLoS	Non Line of Sight
QS	QoS Satisfied
QV	QoS Violated

List of Symbols

$\mathcal{A}$	Closed area under observation
$\mathcal{B}$	Number of BSs
$\mathcal{P}_m$	Maximum downlink transmit power level
$\rho_b(t)$	Traffic intensity at BS b at time t
ζ	Skewness intensity factor
BW_{ub}	Frequency resource allocated to user u by BS b
r_{ub}	Rate achieved at user u by BS b
$\mathcal{P}_{ub}$	Power allocated to user u by BS b
g_{ub}	Channel gain at user u when associated with BS b
σ^2	Power spectral density of AWGN
d_{ub}	Distance of u from BS b
n	Path loss exponent
N_{tr}	Number of transceivers at BS
$\mathcal{P}_0$	Static power consumption by a BS
$\mathcal{E}_b$	Energy consumption by BS b
θ	Constant denoting power amplifier efficiency
N_{PV}	Number of PV panels
N_B	Number of storage batteries
β^{max}	Maximum energy storage capacity at a BS
$\mathbb{B}_c$	Unit battery capacity
β^{cr}	Critical threshold level of battery storage
δ	Depth of discharge
$\beta_b(t)$	Battery level of BS b at time t
$ED(t)$	Number of energy-deficient BSs at t
$ES(t)$	Number of energy-sufficient BSs at t
$\mathcal{D}_b(t)$	Deficit energy at BS b at time t

$\mathcal{E}_b^s$	Sharable green energy available with BS b
$\mathcal{S}_b$	Green energy shared to a BS b
R_{serve}	Revenue earned by serving users
R_{sell}	Revenue earned by selling energy back to grid
C_{share}	Cost incurred in sharing energy among the BSs
C_{buy}	Cost incurred in procuring energy from grid
$CAPEX$	Capital expenditure incurred
C^{buy}	Price of buying unit energy from power grid
$\mathcal{G}_b$	Grid energy procured from power grid
τ	Delay budget
p^{pler}	Packet loss error rate budget
C^{sh}	Price of unit energy sharing using grid infrastructure
C^{sell}	Price of selling unit energy back to grid
C^{ser}	User service revenue price
$\mathcal{E}_b^{sell}$	Amount of energy sold to grid by BS b
θ_{th}	QoS rate guarantee
π_{ub}	User-BS association indicator variable
λ_u	User density
p_0	Non-outage probability
$\mathcal{R}_b$	Coverage area of BS b
$\mathcal{L}_{PV}$	Lifetime of unit PV panel
$\mathcal{L}_B$	Lifetime of unit battery