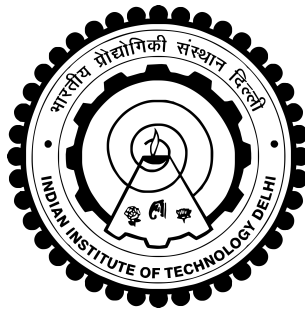


UAV-AIDED RF ENERGY TRANSFER TOWARDS SUSTAINABLE IOT NETWORKS

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2020**

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by

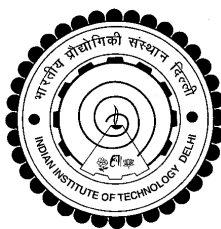
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Certificate

This is to certify that the dissertation entitled **UAV-aided RF Energy Transfer Towards Sustainable IoT Networks**, submitted by **Mr. Suraj Suman**, 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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A handwritten signature in black ink, appearing to read 'S Suman'.

Suraj Suman

Abstract

The internet traffic is growing very rapidly due to exponential growth in the number of Internet of Things (IoT) devices used in different applications. These devices need to operate perpetually for uninterrupted sensing and data gathering in order to report the undesired events. Finite battery capacity of IoT device is the major hurdle towards its perpetual operation in long run, because they consume appreciable amount of energy during sensing, processing, and communication. Further, the installation of wired electricity infrastructure is not possible everywhere due to security, expenditure, or physical constraints. This is a very crucial factor in the next generation wireless network due to increase in number of IoT devices. To this end, this dissertation aims at the energy replenishment solution to ensure perpetual operation of the IoT network. An unmanned aerial vehicle (UAV)-aided energy replenishment framework is proposed in this dissertation, wherein the UAV is considered to travel and hover above the IoT devices and charge them wirelessly through radio frequency energy transfer (RFET). In this dissertation, the theoretical and the experimental avenues of UAV-aided RFET is explored to investigate the limitations and optimization possibilities in practical deployment.

As a first step, a new channel model for UAV-aided RFET is developed. This model plays a key role in RFET-based recharging of wireless IoT devices. Several representative field environments, such as suburban, urban, dense urban, urban high-rise, and rural agriculture deployment scenarios, are considered. The buildup areas are emulated as per the international telecommunication union radiocommunication sector (ITU-R) recommendations, whereas time varying dynamics of vegetation growth is considered for rural agriculture. The proposed path loss models for suburban and rural agriculture deployment scenarios are validated by conducting Air-to-Ground (AtG) RF transmission experiments.

The developed path loss model is used to design the charging mechanism for the field deployed IoT devices. The notion of RFET zone is defined; the IoT devices located within it this zone can harvest energy from the UAV-mounted transmitter. Then, the effective power harvested at the IoT devices located at different spatial locations is evaluated by considering the impact of shadowing statistics of path loss and non-linear RF-to-direct current conversion efficiency. With these findings, an optimization problem is formulated with an objective of minimizing the total time in a charging cycle, which is comprised of travel time and charging time. Then, three different charging protocols, namely *Voltage-aware Charging Sequence*, *Operational Time-aware Charging Sequence*, and *Iterative*

Charging Sequence, are proposed for performance evaluation in terms of number of healthy sensor nodes in a given deployment area.

To investigate the practical feasibility of AtG RFET, the experimental demonstration is performed by two methods. The transmitter is mounted on a static tripod in the first one, whereas the transmitter is mounted on the bottom of UAV in the second one. The power harvester module is placed below the transmitter, which harvests power from the received RF wave. It is observed that the energy harvested in case of tripod-based AtG RFET set up is comparatively higher than that in case of UAV-based AtG RFET set up. This deviation is caused due to hovering inaccuracy of UAV, which arises due to global positioning system (GPS) error and rotational motion of UAV during mission execution. Based on these experiments, a framework to analyze the hovering inaccuracy of UAV is presented, which comprises of two types of mismatches: *Localization mismatch (LM)* and *Orientation mismatch (OM)*. Also, the impact of hovering inaccuracy on the performance of UAV-aided RFET is investigated using the data collected from experimental setup.

Using the analysis of hovering inaccuracy, the individual as well as joint impact of mismatches on the received power at ground deployed IoT device is characterized. A generalized radiation pattern of UAV-mounted transmitter antenna is considered for this purpose. A total of four cases arise due to two types of mismatches, i.e., *LM* and *OM*. An optimization problem is formulated with the objective of optimizing the system parameters, such as transmit power, hovering altitude, and antenna exponent. To solve this, an algorithm, called *Hovering Inaccuracy-aware Optimal Charging System Design (HI-OCSD)*, is proposed to find the optimal system parameters. It is observed that the received power at the sensor node reduces significantly in presence of hovering inaccuracy as compared to ideal scenario. Further, the effect of *LM* is more severe than that of *OM*.

In the last part, a mitigation strategy to overcome the effect of hovering inaccuracy on UAV-aided RFET is presented. For this purpose, an antenna array is mounted on the bottom of the UAV; this array radiates power over a narrow beam directed towards the sensor node with very high gain. However, the directed beam does not point towards the sensor node due to rotational motion of the UAV, which leads to deviation in the elevation angle. An analytical framework to model this deviation in elevation is presented and its variation is estimated using the data collected through an experimental setup. Then, the optimal system parameters are estimated by formulating an optimization problem. It is observed that the proposed framework significantly mitigates the hovering inaccuracy and the same performance can be achieved with substantially less transmit power level.

सारांश

इंटरनेट ऑफ़ थिंग्स (IoT) उपकरणों का उपयोग विभिन्न अनुप्रयोगों में होने के कारण इसकी संख्या में घातीय वृद्धि हो रही है और इंटरनेट यातायात बहुत तेजी से बढ़ रहा है। निरंतर संवेदन और डेटा एकत्र करने हेतु इन उपकरणों को लगातार और बिना बंद हुए कार्य करना जरूरी है। IoT डिवाइस की सीमित बैटरी क्षमता लंबे समय में स्थायी संचालन में सबसे प्रमुख बाधा है, क्योंकि वे पर्याप्त ऊर्जा की मात्रा का उपभोग संवेदन, प्रसंस्करण और संचार के दौरान करते हैं। साथ ही, तारयुक्त बिजली की बुनियादी व्यवस्था सुरक्षा, खर्च एवं भौतिक बाधाओं के कारण हर जगह संभव नहीं है। IoT उपकरणों की संख्या बढ़ने के कारण अगली पीढ़ी के वायरलेस नेटवर्क में यह बहुत ही गंभीर समस्या होगी। यह शोध-निबंध का उद्देश्य IoT नेटवर्क के सतत संचालन को सुनिश्चित करने के लिए समाधान निकलना है। इस शोध-निबंध में एक मानवरहित हवाई वाहन (UAV)-युक्त ऊर्जा आपूर्ति का तंत्र प्रस्तुत किया गया है, जिसमें UAV, IoT उपकरण के पास पहुंचता है और इसके ऊपर मंडराकर IoT उपकरणों में रेडियो आवृत्ति ऊर्जा हस्तान्तरण (RFET) के द्वारा ऊर्जा प्रवाहित करता है। इस शोध-निबंध में UAV-युक्त डियो आवृत्ति ऊर्जा हस्तान्तरण का सैद्धांतिक और प्रायोगिक पहलुओं का गहन निरीक्षण किया गया है ताकि सामान्य जनजीवन में व्यावहारिक तैनाती होने से पहले इसके बाधाओं को दूर किया जा सके।

सबसे पहले, UAV-युक्त RFET के लिए एक नया चैनल मॉडल विकसित किया गया है। यह मॉडल वायरलेस IoT उपकरणों के RFET-आधारित रिचार्जिंग में एक महत्वपूर्ण भूमिका निभाता है। कई प्रतिनिधि व्यावहारिक तैनाती परिवेश, जैसे उपनगरीय, शहरी, घने शहरी, शहरी उच्च-वृद्धि और ग्रामीण कृषि, के लिए चैनल मॉडल विकसित किया गया है। निर्माणाधीन क्षेत्रों में अंतरराष्ट्रीय दूरसंचार संघ रेडोकॉम संचार क्षेत्र (ITU-R) की सिफारिशों के अनुसार इमारतों का आकर लिया गया है, जबकि कृषि परिवेश में समय के साथ वनस्पति विकास की बदलती गतिकी का भी समावेश किया गया है। इसके साथ ही प्रस्तावित चैनल मॉडल को उपनगरीय और ग्रामीण कृषि परिवेश के लिए वायु से जमीन RFET संचरण प्रयोगों द्वारा सत्यापित किया गया है।

इस नए विकसित चैनल मॉडल का उपयोग IoT उपकरणों को ऊर्जा आपूर्ति के लिए समुचित तंत्र बनाने में किया गया है। RFET जोन की धारणा को परिभाषित किया गया है, जहाँ इस जोन के अंदर आने वाले सभी IoT उपकरणों में ऊर्जा का हस्तान्तरण होगा। इसके उपरान्त, विभिन्न स्थानों पर तैनात IoT उपकरणों में प्रभावी रूप के संचयित ऊर्जा की मात्रा की गणना की गयी है जिसमें विकसित शैडो फेडिंग मॉडल और गैर-रेखीय रेडियो आवृत्ति से एकदिश धारा में परिवर्तित होने की क्षमता को भी समावेशित किया गया है। इन निष्कर्षों के साथ, एक चार्जिंग चक्र में कुल समय को कम करने के उद्देश्य से एक अनुकूलन समस्या तैयार की जाती है, जिसमें यात्रा का समय और चार्जिंग समय शामिल है। फिर, तीन अलग-अलग चार्जिंग प्रोटोकॉल, जैसे वोल्टेज-सचेत चार्जिंग अनुक्रम, शेष परिचालन समय-सचेत चार्जिंग अनुक्रम, और पुनरावृत्ति-सचेत चार्जिंग अनुक्रम, को प्रस्तावित किया गया है और इनके प्रदर्शन को दिए गए परिनियोजन क्षेत्र में स्वस्थ IoT उपकरणों की संख्या के आधार पर मूल्यांकन किया गया है।

वायु से जमीन RFET की साध्यता के निरीक्षण के लिए संचरण प्रयोगों के जरिये RFET की व्यवहारिकता को दो विधियों द्वारा जांचा गया है। पहली विधि में ट्रांसमीटर को एक रॉड में लगाया गया है जिसके दोनों सिरों को तिपाई पर रखा गया है, जबकि दूसरी विधि में UAV के तल में ट्रांसमीटर लगाया गया है। ऊर्जा संचयित करने वाले उपकरण को ट्रांसमीटर के नीचे रखा जाता है, जो की प्राप्त रेडियो आवृत्ति को ऊर्जा में बदलता है। इस प्रयोग से यह पाया गया कि UAV आधारित RFET में तिपाई-आधारित RFET से कम ऊर्जा प्राप्त होती है। यह विचलन मिशन के दौरान UAV की अशुद्धि के कारण होती है, जिसमें लोकेशन असंतुलन और ओरिएंटेशन असंतुलन प्रमुख है। इन प्रयोगों के आधार पर हमने UAV अशुद्धि का विश्लेषण किया है।

UAV अशुद्धि के मॉडल का उपयोग करके UAV-आधारित RFET के प्रदर्शन में उत्पन्न हुयी विषमता के निरीक्षण किया गया है, जिसमें लोकेशन असंतुलन और ओरिएंटेशन असंतुलन के अकेले और सम्मिलित प्रभावों का विश्लेषण प्रस्तुत किया गया है। इसके लिए UAV के ताल में जुड़े एंटेना के सामान्यीकृत विकिरण पैटर्न को लिए गया है। दो प्रकार के असंतुलन यानी लोकेशन असंतुलन और ओरिएंटेशन असंतुलन के कारण कुल चार मामलों का अध्ययन किया गया है। श्रेष्ठ सिस्टम के चुनाव के उद्देश्य से एक अनुकूलन समस्या तैयार की जाती है और सिस्टम सम्बंधित कई मापदंडों, जैसे कि ऊर्जा संचरण की मात्रा, UAV की ऊँचाई, और एंटीना, का उपयुक्त चुनाव किया जाता है। इस क्रम में, एक एल्गोरिथ्म जिसका नाम होवरिंग अशुद्धि-जागरूक ऑप्टिमल चार्जिंग सिस्टम डिजाइन कहा गया है (HI-OCSD), प्रस्तावित किया गया है। विश्लेषण के उपरांत यह पाया गया कि IoT उपकरण पर प्राप्त ऊर्जा आदर्श परिवेश की तुलना में UAV अशुद्धि के कारण काफी कम हो जाती है। इसके अलावा, लोकेशन असंतुलन का प्रभाव ओरिएंटेशन असंतुलन की तुलना में अधिक गंभीर है।

अंत में, पिछले भाग में UAV अशुद्धि के कारण हुए नुकसान को कम करने के लिए एक अशुद्धि अल्पीकरण रणनीति प्रस्तुत किया गया है। इस प्रयोजन के लिए, एंटेना के समूह को UAV के तल में जोड़ा जाता है जो एक संकीर्ण किरण IoT उपकरण की ओर निर्देशित करता है। हालाँकि, ओरिएंटेशन असंतुलन के कारण संकीर्ण किरण बिचलित हो जाती है जिससे कि एलिवेशन कोण में विचलन होता है। इस विचलन को मॉडल करने के लिए एक विश्लेषणात्मक रूपरेखा प्रस्तुत की गई है और UAV के प्रायोगिक सेटअप के माध्यम से एकत्र किए गए डेटा का उपयोग करके इसे मॉडल किया गया है। इसके बाद, अनुकूलन समस्या का निर्माण करके उपयुक्त सिस्टम मापदंडों का अनुमान लगाया जाता है। यह पाया गया कि प्रस्तावित अशुद्धि अल्पीकरण रणनीति, अशुद्धि को कम करता है और एक ही प्रदर्शन काफी कम संचारित ऊर्जा स्तर के साथ प्राप्त किया जा सकता है।

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List of Symbols

P_{tx}	Power transmitted by transmitter mounted on UAV
f	Frequency of transmitted RF wave from transmitter mounted on UAV
λ	Wavelength of transmitted RF wave from transmitter mounted on UAV
c	Velocity of light in vacuum
$\mathcal{X}$	Excess path loss
θ	Elevation angle between transmitter and receiver
μ	Mean of a random variable
σ	Standard deviation of a random variable
L	Total path loss
L_{fs}	Free space path loss
$H_P(t)$	Plant height after t days of sowing
p_{LoS}	Line-of-sight probability
p_{nLoS}	Non-line-of-sight probability
h	Hovering altitude of UAV
$\mathbb{E}$	Expectation operator
$\mathcal{N}$	Normal distribution
$R_{RFETzone}$	Radius of RFET zone
G_{rx}	Receiver antenna gain
G_{tx}	Transmitter antenna gain
Q	CCDF of standard univariate normal distribution
N_S	Number of sensors deployed in a given area
A	Deployment area

$P_{\mathcal{H}}(\rho)$	Harvested power for a received power level ρ
P_{sen}	Effective power harvested at the sensor node
P_o	Sensitivity of power harvester
$q_{\mathcal{H}}$	Probability of energy transfer
$v_F^k(\dots)$	Final voltage level of k^{th} supercapacitor
$v_I^k(\dots)$	Initial voltage level of k^{th} supercapacitor
$v_{th}^k(\dots)$	Threshold voltage level of k^{th} supercapacitor
$v_{max}^k(\dots)$	Maximum allowable voltage level of k^{th} supercapacitor
p_c	Charging rate of supercapacitor
p_d	Discharging rate of supercapacitor
C_C	Capacitance of supercapacitor embedded with harvester circuit
R_C	Equivalent series resistance of harvester circuit
Φ_{LM}	Elevation angle between transmitter and receiver due to Localization mismatch
Φ_{OM}	Elevation angle between transmitter and receiver due to Orientation mismatch
Θ	Elevation angle between transmitter and receiver including both mismatches
d_{tx-rx}	Distance between transmitter and receiver
Ψ	Deviation in elevation angle
P_{cov}	Coverage probability
N	Numner of antenna elements in antenna array

List of Abbreviations

UAV	Unmanned Aerial Vehicle
IoT	Internet of Things
WSN	Wireless Sensor Network
AtG	Air-to-Ground
WPT	Wireless Power Transfer
RF	Radio Frequency
RFET	Radio Frequency Energy Transfer
RF-to-DC	Radio Frequency to Direct Current
WCV	Wireless Charging Vehicle
GPS	Global Positioning System
GCS	Ground Control Station
LoS	Line-of-Sight
NLoS	Non-Line-of-Sight
CDF	Cummulative Distribution Function
TSP	Travelling Salesman Problem
VCS	Voltage-aware Charging Sequence
TCS	Operational Time-aware Charging Sequence
ICS	Iterative Charging Sequence
LM	Localization Mismatch
OM	Orientation Mismtach
HI-OCSD	Hovering Inaccuracy-aware Optimal Charging System Design
RMSE	Root Mean Square Error
B5G	Beyond 5G
RFID	Radio Frequency Identification