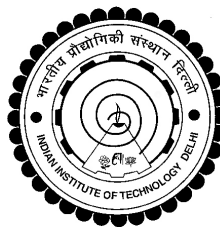


OPTIMAL NODE DESIGN STRATEGIES FOR ENERGY HARVESTING WIRELESS SENSOR NETWORKS

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October 2018**

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by

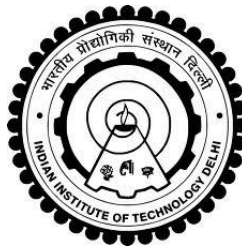
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Certificate

This is to certify that the dissertation entitled **Optimal Node Design Strategies for Energy Harvesting Wireless Sensor Networks**, submitted by **Mr. K Kaushik**, 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 the research claims in the dissertation has been submitted for any degree or academic award elsewhere.

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K Kaushik

Abstract

The first step towards reducing air pollution is to measure the pollution level frequently with a high spatial resolution. High-resolution spatio-temporal maps of air pollution aid in pinpointing the source of pollution and designing effective policies to reduce the pollution. However, as tremendous cost involved is in the set-up of a pollution monitoring station, its density is low. A potential solution is to complement the existing pollution monitoring stations with a densely deployment of low-cost, battery-powered air pollution monitoring wireless sensor nodes such that a fine-grained readings of pollution can be captured with good accuracy.

As the low-cost air pollution monitoring sensors are quite energy hungry, they drain the batteries of a node faster and thereby reduce the lifetime of the deployed wireless sensor network (WSN). Therefore, they need to be replenished frequently if they are expected to operate continuously. Out of the existing energy sources for harvesting energy, Radio Frequency (RF) energy does not depend on environmental factors and is available either from an ambient or a dedicated RF source on-demand. Significant energy of a node can be saved by employing an Integrated Data and Energy MULE (IDEM) to charge the nodes via a dedicated RF source and collect data from them directly. However, for planning the path of IDEM for an uninterrupted operation of the WSN, a critical task is to investigate the components of energy consumed by a node in different activities. To this end, an extensive study on the energy consumptions with a few chosen pollution sensor examples was conducted. Based on the energy consumption and rectification parameters, the required recharging periodicity is derived. After the results are quantified, avenues are presented by where the cost of an RF energy harvesting wireless sensor node and the IDEM cost can be reduced to aid the scalability of the WSN.

Due to the factors such as, upper limit on the RF transmit power, path loss, fading, and low RF-DC efficiency of harvester at low input RF powers, the amount of harvested power by a node is low. Therefore, IDEM takes a long time to charge a single node which may be in the order of a few 10's of minutes. This mandates us to use multiple such IDEM's to achieve a perpetual operation and thus increases the cost of deploying such a WSN. Methods to increase the RF transfer efficiency are needed in order to make RF energy transfer more attractive. One way to achieve this is by transferring the excess energy harvested by an intermediate node to charge a remote node faster through multiple hops. Energy gains that can be realized by this multi-hop energy transfer (MHET) scheme are

quantified through experimental studies. Furthermore, experiments are also performed to find the optimal position where the intermediate node has to be placed for realizing high gains in MHET. Finally, it is also shown that the energy gain obtained can be translated to energy transfer range extension.

An IDEM can serve a higher number of nodes in an IDEM-based WSN if node's energy last longer. To this effect, wake-up receiver (WuRx) is a promising hardware solution that extends the life of a sensor node by switching off its radio to reduce idle listening energy consumption. On this front, one aspect of the thesis is design of cost-effective and long range WuRx solutions for range-based wake-up (RW) as well as directed wake-up (DW). In particular, an RF energy harvesting wireless sensor node is considered and it is investigated how a low-cost WuRx can be built using an RF energy harvester available at the node. Experimental results show that the developed prototype can achieve a wake-up range of 1.16 m with +13 dBm transmit power. Further, through empirical study it is shown that at +30 dBm transmit power the wake-up distance of the developed RW module is > 9 m. Additionally, high accuracy of DW is demonstrated by sending a 5-bit ID from a transmitter at a bit rate up to 33.33 kbps. Finally, optimized WuRx designs are presented for RW and DW using Agilent advanced design system, which offer up to 5.69 times higher wake-up range for RW and energy savings per bit of about 0.41 mJ and 21.40 nJ, respectively, at the transmitter and the sensor node in DW.

Although a sustainable node operation can be achieved by employing an RF Energy source, it is not cost-effective solution when there are multiple high energy consuming pollution sensors on-board. Since the solar energy has the highest density among other harvesting sources, it serves as a potential ambient energy source in such scenarios and also satisfies the high energy demand posed by applications with higher Quality of Service (QoS) requirements. To address this requirement the practical feasibility of sustainable green sensor network is investigated with solar-powered nodes. On this front, simple yet efficient analytical circuit model is proposed for solar panel assisted supercapacitor charging, and statistical model is developed for characterizing the solar intensity distribution. Combining these circuit and statistical models, a novel solar charging rate distribution is derived for the solar-powered supercapacitor. The derived solar charging rate distribution is used to investigate the energy outage probability of a sensor node for a given sensing rate. Further, the proposed models are used to estimate the practical supercapacitor and the required solar panel sizes to ensure sustainability of sensor node operation at different geographical locations with varying sensing rate.

सार

वायु प्रदूषण को कम करने की दिशा में पहला कदम उच्च स्थानिक संकल्प के साथ प्रदूषण स्तर को अक्सर मापना है। प्रदूषण के स्रोत को इंगित करने और प्रदूषण को कम करने के लिए प्रभावी नीतियों को डिजाइन करने में वायु प्रदूषण सहायता के उच्च-रिज़ॉल्यूशन स्पैतिओ-टेम्पोरल मानचित्र। हालांकि, प्रदूषण निगरानी स्टेशन की स्थापना में जबरदस्त लागत शामिल है, इसकी घनत्व कम है। संभावित प्रदूषण निगरानी स्टेशनों को कम लागत वाली, बैटरी संचालित वायु प्रदूषण निगरानी वायरलेस सेंसर नोड्स की घनी तैनाती के साथ मौजूदा प्रदूषण निगरानी स्टेशनों का पूरक करना है, ताकि प्रदूषण के सुगंधित रीडिंग को अच्छी सटीकता से पकड़ा जा सके।

चूंकि कम लागत वाली वायु प्रदूषण निगरानी सेंसर काफी भूख लगी है, इसलिए वे नोड की बैटरी को तेज़ी से निकाल देते हैं और इस तरह तैनात वायरलेस सेंसर नेटवर्क (डब्लूएसएन) के जीवनकाल को कम करते हैं। इसलिए, अगर उन्हें लगातार काम करने की उम्मीद है तो उन्हें अक्सर भरने की जरूरत है। कटाई ऊर्जा के लिए मौजूदा ऊर्जा स्रोतों में से, रेडियो फ्रीक्वेंसी (आरएफ) ऊर्जा पर्यावरणीय कारकों पर निर्भर नहीं है और मांग या मांग पर एक समर्पित आरएफ स्रोत से उपलब्ध है। एक नोड की महत्वपूर्ण ऊर्जा एक समर्पित डेटा और ऊर्जा एमयूएलई (आईडीईएम) को एक समर्पित आरएफ स्रोत के माध्यम से नोड्स चार्ज करने और सीधे डेटा एकत्रित करके सहेजा जा सकता है। हालांकि, डब्लूएसएन के एक निर्बाध संचालन के लिए आईडीईएम के पथ की योजना बनाने के लिए, एक महत्वपूर्ण कार्य विभिन्न गतिविधियों में नोड द्वारा खपत ऊर्जा के घटकों की जांच करना है। इस अंत में, कुछ चयनित प्रदूषण सेंसर उदाहरणों के साथ ऊर्जा खपत पर एक व्यापक अध्ययन आयोजित किया गया था। ऊर्जा खपत और सुधार पैरामीटर के आधार पर, आवश्यक रिचार्जिंग आवधिकता व्युत्पन्न होती है। परिणाम प्रमाणित होने के बाद, रास्ते जहां आरएफ ऊर्जा कटाई वायरलेस सेंसर नोड की लागत और आईडीईएम लागत की लागत डब्लूएसएन की स्केलेबिलिटी की सहायता के लिए कम किया जा सकता है।

कम इनपुट आरएफ शक्तियों पर आरएफ ट्रांसमिट पावर, पथ हानि, लुप्तप्राय, और कम आरएफ-डीसी दक्षता पर उच्च सीमा जैसे कारकों के कारण, नोड द्वारा कटाई की शक्ति कम होती है। इसलिए, आईडीईएम को एक नोड चार्ज करने में काफी समय लगता है जो कुछ 10 मिनट के क्रम में हो सकता है। यह हमें एक सतत संचालन प्राप्त करने के लिए कई ऐसे आईडीईएम का उपयोग करने के लिए अनिवार्य करता है और इस प्रकार इस तरह के डब्लूएसएन को तैनात करने की लागत में वृद्धि करता है। आरएफ ऊर्जा हस्तांतरण को और अधिक आकर्षक बनाने के लिए आरएफ हस्तांतरण दक्षता बढ़ाने के तरीके आवश्यक हैं। इसे प्राप्त करने का एक तरीका अतिरिक्त ऊर्जा को स्थानांतरित करना है कई हॉप के माध्यम से एक दूरस्थ नोड को तेज़ी से चार्ज करने के लिए एक मध्यवर्ती नोड द्वारा कटाई। ऊर्जा लाभ जो इस बहु-हॉप ऊर्जा हस्तांतरण (एमएचईटी) योजना द्वारा महसूस किया जा सकता है प्रयोगात्मक अध्ययन के माध्यम से मात्राबद्ध किया जाता है। इसके अलावा, इष्टतम स्थिति को खोजने के लिए प्रयोग भी किए जाते हैं जहां एमएचईटी में उच्च लाभ को महसूस करने के लिए इंटरमीडिएट नोड रखा जाना चाहिए। अंत में, यह भी दिखाया गया है कि प्राप्त ऊर्जा लाभ का अनुवाद ऊर्जा हस्तांतरण सीमा विस्तार में किया जा सकता है।

आईडीईएम आधारित डब्लूएसएन में नोड की उच्च संख्या में नोड्स की सेवा कर सकते हैं ऊर्जा लंबे समय तक चलती है। इस प्रभाव के लिए, वेक-अप रिसीवर (वूआरएक्स) एक आशाजनक हार्डवेयर समाधान है जो निष्क्रिय रेडियो ऊर्जा खपत को कम करने के लिए अपने रेडियो को बंद करके एक सेंसर नोड का जीवन बढ़ाता है। इस मोर्चे पर, थीसिस का एक पहलू रेंज-आधारित वेक-अप (आरडब्ल्यू) के साथ-साथ निर्देशित वेक-अप (डीडब्लू) के लिए लागत प्रभावी और लंबी दूरी के वूआरएक्स समाधानों का डिज़ाइन है। विशेष रूप से, एक आरएफ ऊर्जा कटाई वायरलेस सेंसर नोड माना जाता है और यह जांच की जाती है कि नोड पर उपलब्ध आरएफ ऊर्जा हारवेस्टर का उपयोग करके कम लागत वाला वूआरएक्स कैसे बनाया जा सकता है। प्रायोगिक परिणामों से पता चलता है कि विकसित प्रोटोटाइप जागृत हो सकता है +13 डीबीएम ट्रांसमिट पावर के साथ 1.16 मीटर की रेंज। इसके अलावा, अनुभवजन्य अध्ययन के माध्यम से यह दिखाया गया है कि +30 डीबीएम ट्रांसमिट शक्ति पर विकसित आरडब्ल्यू मॉड्यूल की जागृत दूरी > 9 मीटर है। इसके अतिरिक्त, डीडब्ल्यू की उच्च सटीकता का प्रदर्शन ट्रांसमीटर से 5-बिट आईडी को 33.33 केबीपीएस तक थोड़ा सा दर पर भेजकर किया जाता है। अंत में, ऑप्टिमाइज्ड वूआरएक्स डिज़ाइन आरडब्ल्यू और डीडब्ल्यू के लिए एजिलेंट एडवांस्ड डिज़ाइन सिस्टम का उपयोग करके प्रस्तुत किए जाते हैं, जो ट्रांसमीटर पर क्रमशः 0.41 एमजे और 21.40 एनजे प्रति आरडब्ल्यूड ऊर्जा बचत के लिए 5.69 गुना अधिक जागने की रेंज प्रदान करते हैं। डीडब्ल्यू में सेंसर नोड।

हालांकि आरएफ एनर्जी स्रोत को नियोजित करके एक टिकाऊ नोड ऑपरेशन हासिल किया जा सकता है, लेकिन यह लागत प्रभावी समाधान नहीं है जब बोर्ड पर कई उच्च ऊर्जा उपभोग प्रदूषण सेंसर होते हैं। चूंकि सौर ऊर्जा अन्य कटाई स्रोतों के बीच उच्चतम घनत्व है, इसलिए यह ऐसे परिदृश्यों में संभावित परिवेश ऊर्जा स्रोत के रूप में कार्य करता है और उच्च गुणवत्ता की सेवा (क्यूओएस) आवश्यकताओं के साथ अनुप्रयोगों द्वारा उत्पन्न उच्च ऊर्जा मांग को भी पूरा करता है। इस आवश्यकता को हल करने के लिए टिकाऊ हरे सेंसर नेटवर्क की व्यावहारिक व्यवहार्यता की जांच सौर-संचालित नोड्स के साथ की जाती है। इस मोर्चे पर, अभी तक सरल सौर पैनल सहायक सुपरकेपिसिटर चार्जिंग के लिए कुशल विश्लेषणात्मक सर्किट मॉडल का प्रस्ताव है, और सौर मॉडल वितरण की विशेषता के लिए सांख्यिकीय मॉडल विकसित किया गया है। इन सर्किट और सांख्यिकीय मॉडल का मिश्रण, सौर ऊर्जा संचालित सुपरकेपिसिटर के लिए एक उपन्यास सौर चार्जिंग दर वितरण प्राप्त किया गया है। व्युत्पन्न सौर चार्जिंग दर वितरण का उपयोग किसी दिए गए सेंसिंग के लिए सेंसर नोड की ऊर्जा आउटपुट संभावना की जांच के लिए किया जाता है मूल्यांकन करें। इसके अलावा, प्रस्तावित मॉडल का प्रयोग व्यावहारिक सुपरकेपिसिटर और आवश्यक सौर पैनल आकार का अनुमान लगाने के लिए किया जाता है ताकि अलग-अलग भौगोलिक स्थानों पर सेंसर नोड ऑपरेशन की स्थिरता सुनिश्चित हो सके।

Contents

List of Figures	iv
List of Tables	vi
List of Acronyms	viii
List of Symbols	x
1 Introduction	1
1.1 Background Literature	1
1.2 Motivation	6
1.3 Background Studies Leading to the Dissertation	7
1.3.1 Perpetual Operation of RF Energy Harvesting WSN	8
1.4 Scope and Practical Utility	15
1.5 Organization	16
2 Experimental Proof-of-Concept on RF Energy Transfer	18
2.1 Introduction	18
2.1.1 Related Work	20
2.1.2 Motivation	21
2.1.3 Scope and Contributions	22
2.1.4 Chapter Organization	22
2.2 Two-hop Energy Transfer	23
2.2.1 Algorithm for Efficient operation of Intermediate node	25
2.2.2 Experimental Results	27
2.3 Summary	35

3	RF Energy Harvester-based Wake-up Receiver Design	36
3.1	Introduction	36
3.1.1	Related Works	37
3.1.2	Motivation	38
3.1.3	Scope and Contributions	39
3.1.4	Organization	40
3.2	Proposed RFEH-based WuRx Design	40
3.2.1	Attributes of RFEH	41
3.2.2	Comparison of 7-Stage RFEH with Powercast P1110	41
3.2.3	Prototype of RFEH-based WuRx	42
3.3	Range-based Wake-up	43
3.3.1	Implementation	44
3.3.2	Experimental Results for RW	44
3.4	Directed Wake-up	45
3.4.1	Implementation	45
3.4.2	Experimental Study	46
3.4.3	Experimental Results for DW	47
3.5	Empirical Model for Estimating Wake-up Range	48
3.5.1	Variation of $V_{\text{int}}^{\text{min}}$ with Supply Voltage of Mote	49
3.5.2	Current Consumption Comparison of RW Scheme	50
3.5.3	Relationship between Wake-up Range and Transmit Power	51
3.6	Summary	52
4	Long-Range Wake-up Receiver Design for Generic Wireless Sensor Network	53
4.1	Introduction	53
4.1.1	Background	54
4.1.2	Contributions and Chapter Organization	56
4.2	Powercast P1110 RFEH-WuRx Enabled Sensor Node	57
4.2.1	Field Node Architecture	57
4.2.2	Operation	59
4.3	Optimized WuRx Design	59
4.3.1	Effect of Stage Capacitor C_{stage}	60
4.3.2	Effect of Matching Circuit (C_m, L_m) and Number of Stages	61
4.3.3	Wake-up Speed Versus Range Tradeoff in DW	63

4.4	Summary	65
5	Stochastic Solar Harvesting Characterization for Sustainable Node Operation	67
5.1	Introduction	67
5.1.1	Related Works	68
5.1.2	Motivation and Scope	69
5.1.3	Contributions and Organization	69
5.2	System Model and Problem Definition	70
5.2.1	Network Architecture and Energy Consumption Model	71
5.2.2	Solar Powered Communication	71
5.3	Solar Charging Rate Characterization	72
5.3.1	Circuit Model	72
5.3.2	Solar Charging Rate for Practical Solar Panel Model	74
5.3.3	Approximate Solar Panel Model	76
5.4	Proposed Solar Intensity Distribution	79
5.4.1	Empirical Dataset for Solar Intensity Profile	79
5.4.2	Polynomial-fit Based Mixture Distribution	79
5.4.3	Validation of Proposed Distribution Model	80
5.5	Stochastic Harvested Energy Characterization and its Applications	81
5.5.1	Solar Charging Rate Distribution	82
5.5.2	Energy Outage Probability (p_{out})	83
5.5.3	Solar Panel Size Estimation	83
5.5.4	Supercapacitor Size Estimation	84
5.6	Performance Evaluation and Discussion	87
5.6.1	Validation of Analysis	87
5.6.2	Energy Outage Probability Versus Sampling Rate Trade-off	89
5.6.3	Results on Sizing the Components	90
5.6.4	Discussion on Use Cases	91
5.7	Summary	93
6	Conclusion and Future Works	95
6.1	Concluding Remarks	95
6.2	Future Works	97

Bibliography	98
Publications	106
Biodata of the Author	109

List of Figures

1.1	Voronoi digram of air pollution monitoring stations in Delhi	2
1.2	Components of RF energy harvesting wireless sensor network	8
1.3	A sensor node's operation states [1].	9
1.4	Energy consumption versus sampling period [1].	10
1.5	Effect of duty cycle [1].	11
1.6	Time of charging versus sampling period assuming IDEM arrives twice a day [1].	12
1.7	Distance versus charging time [1].	12
2.1	Multi-hop Energy Transfer [2].	19
2.2	Experimental setup for two-hop energy transfer.	23
2.3	On-off cycles at the intermediate node.	26
2.4	Experimental setup for finding the optimal position for the intermediate node.	30
2.5	Top view of experimental setup block diagram to find optimal position of intermediate node.	31
3.1	Field sensor node wake-up (RW or DW) state diagram.	40
3.2	Proposed simplified wake-up circuit.	41
3.3	Responsiveness of RFEHs to RF signal input	42
3.4	Prototype of RFEH-based WuRx enabled sensor node.	43
3.5	Effect of transmit power on WuRx range.	44
3.6	Directed wake-up timing diagram for ID = 101.	45
3.7	Directed wake-up.	47
3.8	Decoding accuracy versus bit duration.	48
3.9	Minimum voltage for triggering various motes.	49

3.10	Current consumed by interrupt pin.	50
3.11	Characteristic of our used RFEH.	51
3.12	Wake-up range (in m), indicated by numbers in the graph.	51
4.1	ADS simulation block diagram of RFEH using a 7-stage Dickson voltage multiplier.	54
4.2	Block diagram of field node with Powercast P1110 RFEH	58
4.3	Effect of C_{stage} value on t_{rise} and t_{fall} . $R_l = 220 \text{ M}\Omega$, $C_m = 3.3 \text{ pF}$, $L_m = 68 \text{ nH}$, stages = 7, $P_r^{\text{min}} = -3.4 \text{ dBm}$ for $V_{\text{out}}^{\text{DC}} = 2.2 \text{ V}$	61
4.4	Effect of stages. $C_{\text{stage}} = 9 \text{ pF}$, $R_l = 220 \text{ M}\Omega$	62
4.5	Response of different WuRx circuits for RW.	62
4.6	Tradeoff between rise/fall time and wake-up range in DW. Numbers in squared box indicate the number of stages (cf. Table 4.1 for optimum matching parameters (C_m, L_m) and P_r^{min}).	65
5.1	Circuit for charging a supercapacitor using solar panel.	68
5.2	Residue plots for a_1, b_1, c_1	75
5.3	Linear fit for a_1^{new}	76
5.4	Gaussian fitting function for Lambert function of V_C	76
5.5	Output characteristics of solar panel.	77
5.6	Validation of the polynomial-fit based mixture distribution of G	80
5.7	Validation of solar charging rate CDF for different regions.	89
5.8	Sampling rate versus energy outage probability.	89

List of Tables

1.1	Specifications of sensors [1]	9
2.1	Voltage Gain	28
2.2	Time and energy gain	29
2.3	Voltage gain for case A (intermediate node close to source node).	32
2.4	Voltage gain for case B (intermediate node in the middle)	32
2.5	Voltage gain for Case C (intermediate node close to end node)	33
2.6	Time gain for case A (intermediate node close to source node)	33
2.7	Time gain for case B (intermediate node in the middle)	34
2.8	Time gain for case C (intermediate node close to end node)	34
3.1	System specifications.	47
4.1	Effect of number of stages with optimized WuRx for DW. $R_l = 220 \text{ M}\Omega$, $C_{\text{stage}} = 9 \text{ pF}$	64
5.1	System parameters for 3 W panel at STC.	77
5.2	Coefficients of Polynomial function	81
5.3	Voltage and current consumption of Wasp mote components.	88
5.4	Solar panel and supercapacitor sizes	91

List of Acronyms

ABC	Ambient Backscatter Communication
ACK	Acknowledgment
ADC	Analog to Digital Converter
ASIC	Application Specific IC
BMAC	Berkeley MAC
BTS	Base Transceiver Station
CDF	Cummulative Distribution Function
CH ₄	Methane
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CPCB	Central Pollution Control Board
CPU	Central Processing Unit
DC	Direct Current
DET	Direct Energy Transfer
DW	Directed Wake-up
EH	Energy Harvesting
EIRP	Effective Isotropic Transmit Power
ET	Energy Transfer
GDP	Gross Domestic Product
IC	Integrated Circuit
ID	Identity
IDEM	Integrated Data and Energy MULE
LAN	Local Access Network
LEACH	Low Energy Adaptive Clustering Hirearchy
LOS	Line of Sight

LPM1	Low Power Mode 1
LPM3	Low Power Mode 3
MAC	Medium Access Control
MCU	Micro Controller Unit
MHET	Multi Hop Energy Transfer
MPER	Multi Path Energy Routing
MULE	Mobile Ubiquitous LAN Extension
NAAQS	National Ambient Air Quality Standards
NH ₃	Ammonia
NO ₂	Nitrogen Dioxide
NREL	National Renewable Energy Laboratory
OOK	On Off Keying
QoS	Quality of Service
PDF	Probability Density Function
PWN	Perpetual Wireless Network
QoS	Quality of Service
WSN	Wireless Sensor Network
REACH	Range Enhancing Energy Harvester
RF	Radio Frequency
RFEH	Radio Frequency Energy Harvester
RFET	Radio Frequency Energy Transfer
RFID	Radio Frequency Identity
RMSE	Root Mean Square Error
RW	Range-based Wake-up
RZ	Return to Zero
SMAC	Synchronous MAC
STC	Standard Testing Conditions
TI	Texas Instruments
VOC	Volatile Organic Compounds
WARP	Wireless Ambient Radio Power
WISP	Wireless Identification and Sensing Platform
WHO	World Health Organisation
WuRx	Wake-up Receiver
WuTx	Wake-up Transmitter
WSN	Wireless Sensor Network

List of Symbols

$V_{\text{int}}^{\text{min}}$	Minimum interrupt voltage
$V_{\text{out}}^{\text{DC}}$	Output voltage of RFEH
$P_{\text{r}}^{\text{min}}$	Minimum input RF power for interrupt detection
T_b	Duration of one bit
N	Length of node ID
V_{cc}	Supply voltage of MCU
V_{mote}	Mote Supply Voltage
$V_{\text{int}}^{\text{min, TI}}$	Minimum interrupt voltage needed by TI-mote
I_{int}	Current consumed by interrupt pin
$P_{\text{r}}^{\text{min, TI}}$	Minimum input RF power for interrupt detection on TI-mote
$P_{\text{r}}^{\text{min, W}}$	Minimum input RF power for interrupt detection on Waspote
$V_{\text{int}}^{\text{min, W}}$	Minimum interrupt voltage required by Waspote
λ	Wavelength
P_{t}	Power Transmitted
P_{r}	Power Received
G_{t}	Transmitter antenna gain
G_{r}	Receiver antenna gain
$V_{\text{mote}}^{\text{rec, l}}$	lower limit of recommended operating voltage of mote
$V_{\text{mote}}^{\text{rec, u}}$	upper limit of recommended operating voltage of mote
R_{SET}	Configuration Resistor
R_{on}	On resistance of electronic switch
$R_{\text{SET}}^{\text{W}}$	Configuration resistor for wake-up operation
$R_{\text{SET}}^{\text{C}}$	Configuration resistor for charging operation

R_{pd}	Pulldown resistor
C_{stage}	Stage capacitor
R_l	Load resistor
C_m	Matching circuit capacitor
L_m	Matching circuit inductor
t_{rise}	Rise time
t_{fall}	Fall time
t_{detect}	Interrupt detection time
D_1	External diode
D_2	Internal diode
D_c	Sensing duty-cycle
N_{sn}	Number of on-board sensors
r_s	Sensing rate in samples per day
$t_r^{N_{sn}}$	Sum of response times of N_{sn} sensors
t_w	time for logging one sensor sample
t_d	Duration of a day in seconds
P_{cons}^{avg}	Average power consumption of a sensor node
f_{ent}	Frequency of arrival of mobile entity
$P_{se}^{N_{sn}}$	Average power consumption for N_{sn} sensors during sensing
P_w	Average power consumption during data logging
P_{sl}	Average power consumption during sleep state
P_o	Average power consumption during communication
t_o	Average time for communication
G	Solar Intensity
N_S	Number of series connected solar cells
R_S	Series resistance
R_S^{STC}	Series resistance at STC
R_P	Shunt Resistance
R_P^{STC}	Shunt Resistance at STC
I_M	Output solar panel current
V_M	Output solar panel voltage
Γ	Solar charging rate

Γ_a	Solar charging rate for approximate solar panel model
Γ_p	Solar charging rate for practical solar panel model
p_{out}	energy outage probability
C	Supercapacitor value
V_x^{ext}	Cut-off voltage for D_1
V_x^{int}	Cut-off voltage for D_2
T	Solar cell temperature in kelvin
T^{STC}	Solar cell temperature at STC in kelvin
V_{OC}	Open circuit voltage
I_{SC}	Short circuit current
V_{mp}	Voltage at maximum power point
I_{mp}	Current at maximum power point
k	Boltzmann's constant
q	Charge of electron
I_0	Reverse saturation current
I_0^{STC}	Reverse saturation current at STC
n	Ideality factor
n^{STC}	Ideality factor at STC
I_{irr}	Solar current
I_{irr}^{STC}	Solar current at STC
α_T'	Relative temperature coefficient of I_{SC}
E_g	Band gap energy
V_C^{max}	Maximum charging voltage of supercapacitor
f_G^{pol}	PDF of G
m	order of polynomial function
q_i	i^{th} coefficient of polynomial
V_{res}	Residual voltage of supercapacitor
F_{Γ_a}	CDF of Γ_a
F_{Γ_p}	CDF of Γ_p
F_G	CDF of G
t	dummy variable for time

V_{load}^{max}	Maximum operable voltage of load
V_{load}^{min}	Minimum operable voltage of load
V_C^{max}	Maximum charging voltage of supercapacitor
V_C^{min}	Minimum charging voltage of supercapacitor
G^{max}	Maximum solar intensity
N_S^p	N_S for practical solar panel model
N_S^a	N_S for approximate solar panel model
C_1	Supercapacitor size for storing excess energy
t_{start}	t at start of daylight time
t_{end}	t at end of daylight time
C_1^u	Upper bound of C_1
C_1^l	Lower bound of C_1
C_2	supercapacitor size to support P_{cons}^{avg} during non-sunlight hours
V_C	supercapacitor voltage