An Energy Efficient, Self-Sustainable, and Long Range IoT System for Drought Monitoring and Early Warning

Prof. Tran Xuan Nam and A/Prof. Hoang Van Phuc
Advanced Wireless Communications Group
Le Quy Don Technical University

Agenda

1. Introduction of research group
2. Project information
3. Post project activities
4. Conclusion and future outlook

Introduction of AWC Group at LQDTU

Advanced Wireless Communication Group
Le Quy Don Technical University

LE QUY DON
Technical University

GROUP MEMBERS

- 5 members of LQDTU
- 4 associate members
- 5 PhD students

RESEARCH AREAS

- Machine learning for communications
- UAV communications
- In-band full-duplex communications.
- Spatial modulation and index modulation.
- Non-orthogonal multiple access (NOMA).
- MIMO and relay communications

CURRENT RESEARCH PROJECTS

- Unmanned Aerial Vehicle (UAV)-to-X Communications for Future Wireless Systems funded by *National Foundation for Science and Technology Development (NAFOSTED)* [2023-2026]
- Rate Splitting Multiple Access for 6G Communications funded by *National Foundation for Science and Technology Development (NAFOSTED)* [2024-2026]

Project Members

VIETNAM

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A/Prof. Hoang Van Phuc (LQDTU, Vietnam)
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Dr. Nguyen Quoc Dinh (LQDTU, Vietnam)
Dr. Nguyen Thuy Linh (LQDTU, Vietnam)
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INTERNATIONAL PARTNERS

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Prof. Jiro Ida (KIT, Japan)

THAILAND

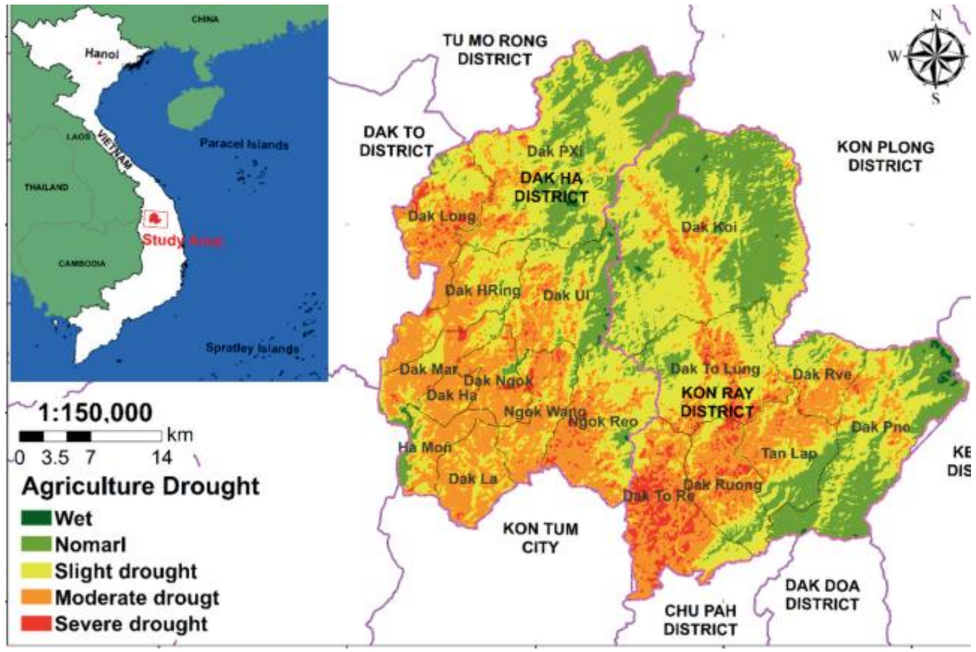
Prof. Kosin Chamnongthai (KMUTT, Thailand)
Prof. Taworn Benjanarasuth (KMITL, Thailand)

SWEDEN

Dr. Dao Van Lan (Malardalen Univ., Sweden)

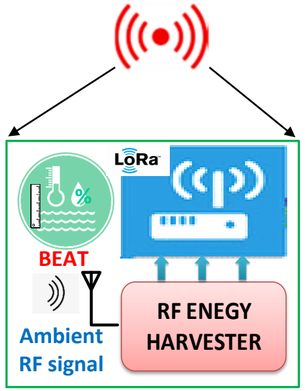
Project Objective

- To develop a real-time, energy efficient, self-sustainable and long range drought monitoring and early warning system based on IoT technology to provide timely warning.
- Specific targets include:
  - Design & implement a real-time IoT based drought monitoring and early warning system to provide a continuous assessment and support decision making process;
  - Investigate the efficiency of using innovative sensors, different energy harvesting techniques and communication protocol for the drought monitoring system.

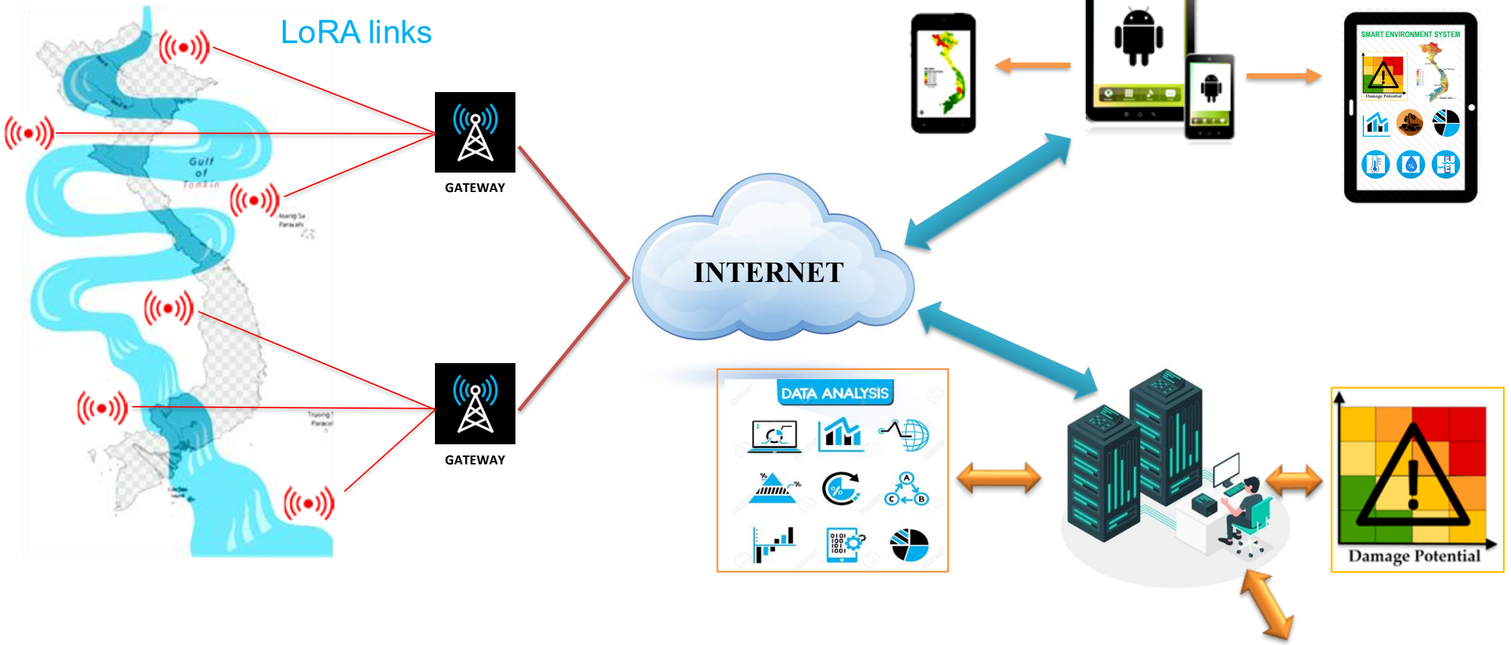


Project Duration: From June 01, 2020 to March 31, 2022

Proposed IoT Monitoring System

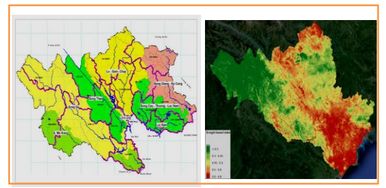


RFEH
beat sensor node



KEY TECHNOLOGIES

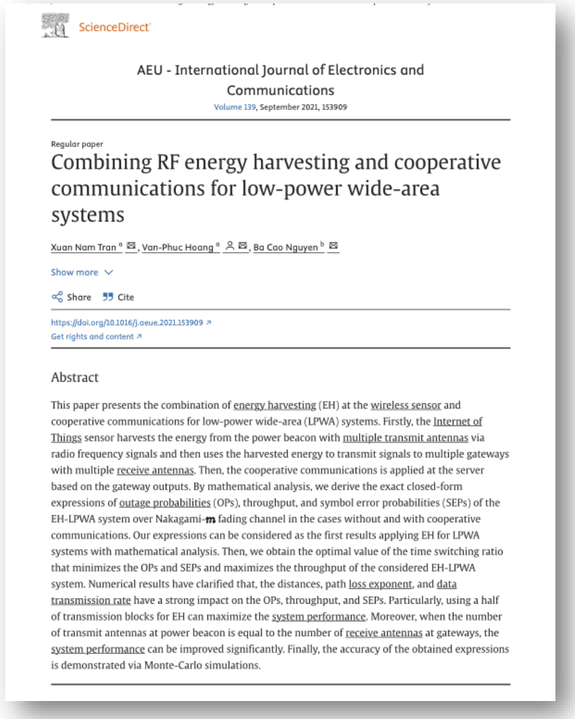
- Using beat sensor node with RF energy harvesting to ensure energy efficiency and self-sustainability.
- Sensing data transmission using LoRA links to provide long-range coverage.



Drought hazard map

Project Activities

Theoretical study



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Volume 139, September 2021, 153909

Regular paper

Combining RF energy harvesting and cooperative communications for low-power wide-area systems

Xuan Nam Tran [a], Van-Phuc Hoang [a], Ba Cao Nguyen [b]

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https://doi.org/10.1016/j.aeue.2021.153909

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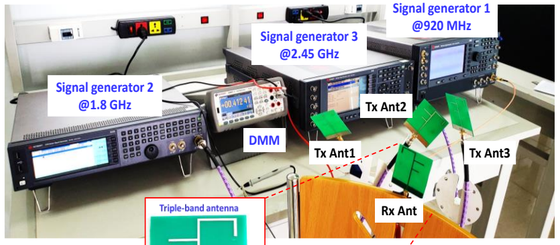
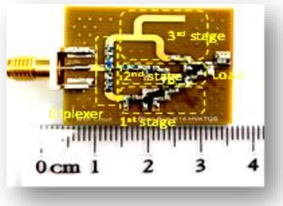
Abstract

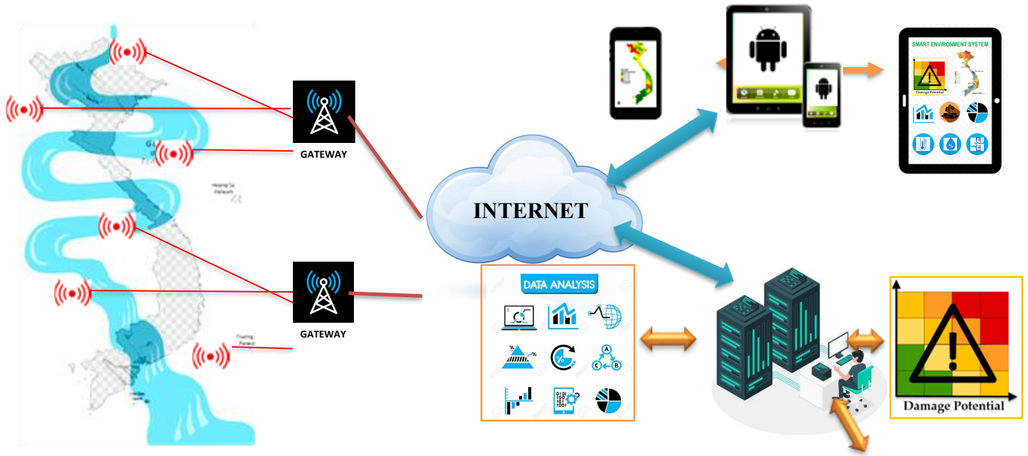
This paper presents the combination of energy harvesting (EH) at the wireless sensor and cooperative communications for low-power wide-area (LPWA) systems. Firstly, the Internet of Things sensor harvests the energy from the power beacon with multiple transmit antennas via radio frequency signals and then uses the harvested energy to transmit signals to multiple gateways with multiple receive antennas. Then, the cooperative communications is applied at the server based on the gateway outputs. By mathematical analysis, we derive the exact closed-form expressions of outage probabilities (OPs), throughput, and symbol error probabilities (SEPs) of the EH-LPWA system over Nakagami-m fading channel in the cases without and with cooperative communications. Our expressions can be considered as the first results applying EH for LPWA systems with mathematical analysis. Then, we obtain the optimal value of the time switching ratio that minimizes the OPs and SEPs and maximizes the throughput of the considered EH-LPWA system. Numerical results have clarified that, the distances, path loss exponent, and data transmission rate have a strong impact on the OPs, throughput, and SEPs. Particularly, using a half of transmission blocks for EH can maximize the system performance. Moreover, when the number of transmit antennas at power beacon is equal to the number of receive antennas at gateways, the system performance can be improved significantly. Finally, the accuracy of the obtained expressions is demonstrated via Monte-Carlo simulations.

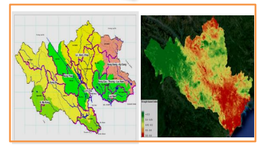
Hardware development





Prototype system implementation

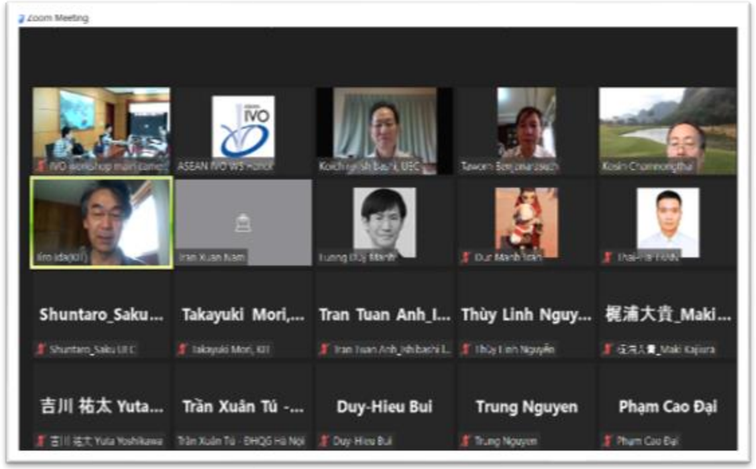




Drought hazard map

Project Outcomes

Workshops and Meetings



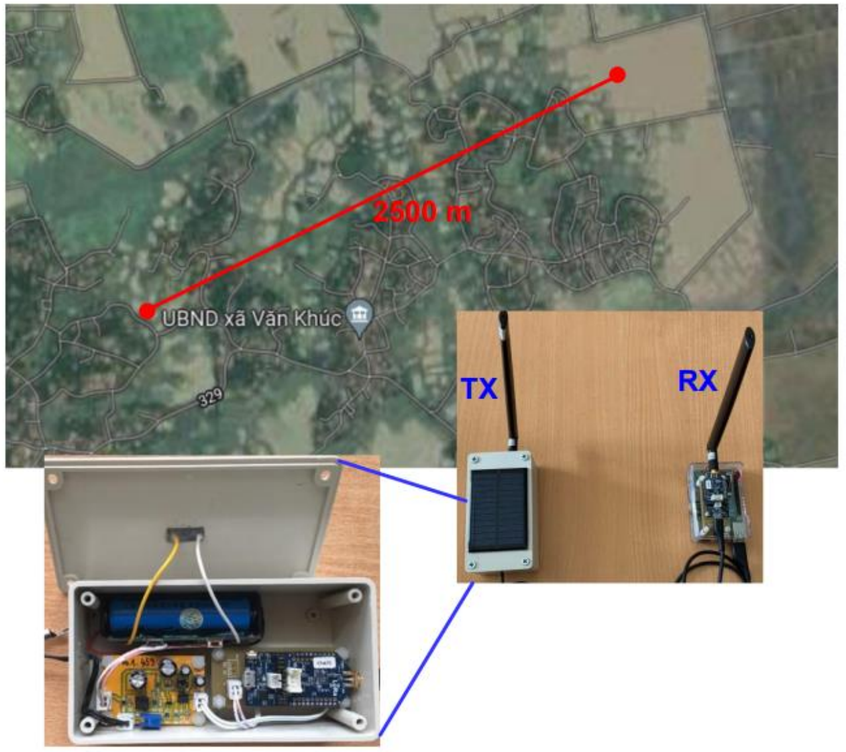
Project Outcomes

Hardware Development

Having developed and field-tested energy-efficient sensors for LoRa communications:

- Using beat sensor for LoRa band (933MHz)
- Communication range: 600 m tested in Tokyo; 1.7 km tested in Hanoi, 2.5 km in Phu Tho province, Vietnam

Field tested in Chofu-shi, Tokyo, Japan
- Maximum range: 600 m



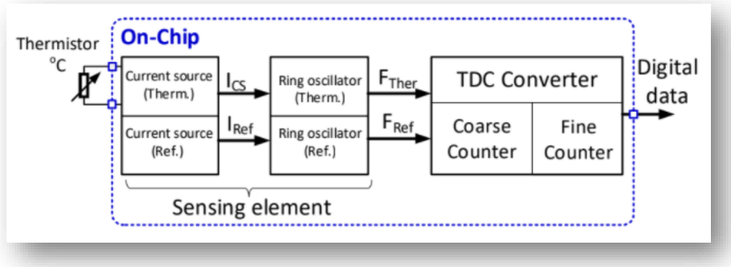
Field test in Vietnam
- Phu Tho province, max range: 2.500 m
- Hanoi city, max range: 1.700m

Project Outcomes

Hardware Development and Field Test

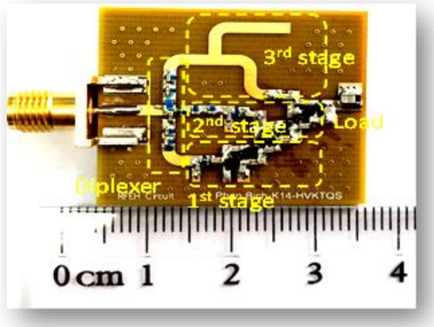
Sensor Development

- Beat sensor for LoRa band @ 933MHz
- Temperature sensor using thermistor-defined TDC
  - 0.07mm^2, 446nW power temperature sensor in 180nm CMOS technology
  - Operation range: -20^{o}C to 80^{o}C
  - Resolution: 0.06^{o}C



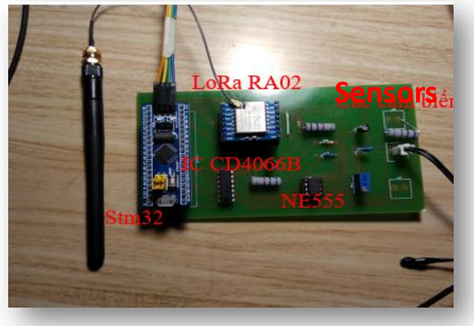
RF Energy Harvesting Circuit

- Concurrent triple-band
- Op. frequency: GSM-900, GSM-1800 and 2.45 GHz
- DC output level: 643mV



Multiple-beat sensor node with RFEH

- Temperature beat sensor
- Humidity beat sensor
- Water level beat sensor



Project Outcomes

Articles and Technical Reports: **2 SCIE/Scopus, 2 conference papers, 1 technical report.**

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journal homepage: www.elsevier.com/locate/aeue

Regular paper

Combining RF energy harvesting and cooperative communications for low-power wide-area systems

Xuan Nam Tran [a], Van-Phuc Hoang [a,*], Ba Cao Nguyen [b]

[a] Le Quy Don Technical University, Ha Noi, Viet Nam
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ARTICLE INFO

Keywords:
Low-power wide-area network
Long range
Energy harvesting
Cooperative communication
Outage probability
Throughput
Symbol error probability

ABSTRACT

This paper presents the combination of energy harvesting (EH) at the wireless sensor and cooperative communications for low-power wide-area (LPWA) systems. Firstly, the Internet of Things sensor harvests the energy from the power beacon with multiple transmit antennas via radio frequency signals and then uses the harvested energy to transmit signals to multiple gateways with multiple receive antennas. Then, the cooperative communications is applied at the server based on the gateway outputs. By mathematical analysis, we derive the exact closed-form expression of outage probabilities (OPs), throughput, and symbol error probabilities (SEPs) of the EH-LPWA system over Nakagami-m fading channel in the cases without and with cooperative communications. Our expressions can be considered as the first results applying EH for LPWA systems with mathematical analysis. Then, we obtain the optimal value of the time switching ratio that minimizes the OPs and SEPs and maximizes the throughput of the considered EH-LPWA system. Numerical results have clarified that, the distances, path loss exponent, and data transmission rate have a strong impact on the OPs, throughput, and SEPs. Particularly, using a half of transmission blocks for EH can maximize the system performance. Moreover, when the number of transmit antennas at power beacon is equal to the number of receive antennas at gateways, the system performance can be improved significantly. Finally, the accuracy of the obtained expressions is demonstrated via Monte-Carlo simulations.

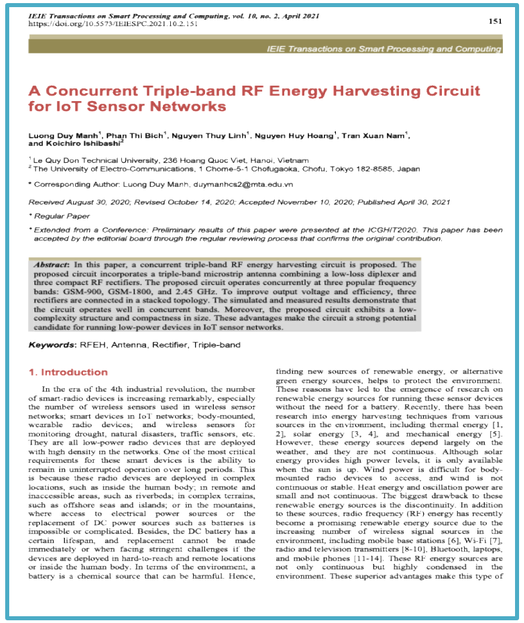
1. Introduction

Recently, energy harvesting (EH) from radio frequency (RF) signals has been widely used to satisfy the energy requirements of wireless communication systems. Hence, it becomes a promising forthcoming technique to be deployed in the fifth generation (5G) and beyond networks [1,2]. Specifically, EH can supply enough power for sensor in Internet of things (IoT) systems, heterogeneous networks (HetNets), mobile devices, and extremely remote area communications. In addition, wireless devices can transmit the RF signals over the air for a long range, thus, EH from RF signals can be applied for many devices that are located in the restricted areas, where the traditional energy grid is extremely difficult to be deployed. For example, RF EH power supply is very promising for IoT based smart environment monitoring systems with energy efficient Beat sensors and LoRaWAN communications [3]. Consequently, the researches and experiments about EH are developed quickly so that we could apply this technique for the current and future wireless systems soon [4–6].

In the literature, the linear and non-linear energy harvesters have been proposed to apply the EH technique for wireless devices [1,7]. In particular, the wireless devices can harvest the energy from base stations [8–10] or power beacons [11]. The mathematical analysis was used to derive the expressions in terms of outage probability (OP), throughput, and symbol error probability (SEP) of the EH communication systems [8,11]. It was shown that for a certain EH system, there is an optimal value of the time switching ratio which can minimize the system OP/SEP. Also, using multiple antennas for the power beacon can greatly improve the performance of EH systems because of a significant increase about the amount of harvested energy. In addition, the non-linear characteristics of energy harvesters cause the power ceiling for the harvested energy leading to a error floor of OP/SEP in EH system [12]. Furthermore, EH technique is combined with various new techniques such as full-duplex (FD), cognitive radio (CR), spatial modulation (SM), and non-orthogonal multiple access (NOMA) for enhancements in both energy and spectral efficiencies [8,11–14]. In addition to the mathematical analysis, the experimental measurements were also used to investigate the amount of harvested energy and the performance of EH communication systems in practice [7,15,16].

* Corresponding author.

Xuan Nam Tran, Van-Phuc Hoang, Ba Cao Nguyen, "Combining RF energy harvesting and cooperative communications for low-power wide-area systems," *AEU International Journal of Electronics and Communications,* ISSN 1434-8411, vol.139, Sept. 2021.



IEIE Transactions on Smart Processing and Computing, vol. 10, no. 2, April 2017
https://doi.org/10.5573/IEIESPC.2021.10.2.151 151

IEIE Transactions on Smart Processing and Computing

A Concurrent Triple-band RF Energy Harvesting Circuit for IoT Sensor Networks

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[2] The University of Electro-Communications, 1 Chome-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan

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* *Regular Paper*

* *Extended from a Conference: Preliminary results of this paper were presented at the ICGHIT2020. This paper has been accepted by the editorial board through the regular reviewing process that confirms the original contribution.*

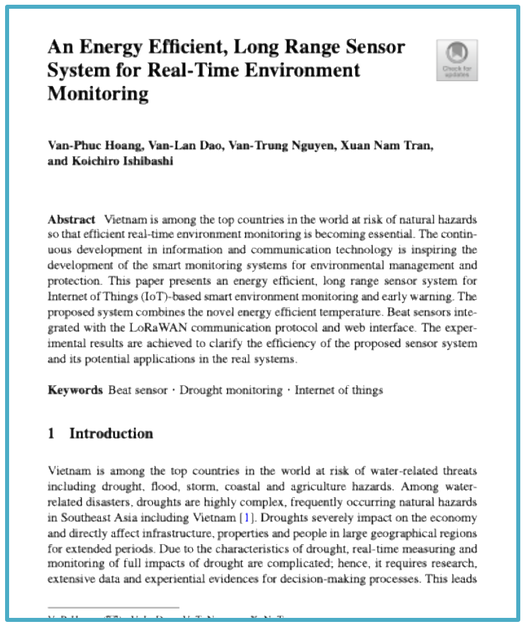
Abstract: In this paper, a concurrent triple-band RF energy harvesting circuit is proposed. The proposed circuit incorporates a triple-band microstrip antenna combining a low-loss diplexer and three compact RF rectifiers. The proposed circuit operates concurrently at three popular frequency bands: GSM-900, GSM-1800, and 2.45 GHz. To improve output voltage and efficiency, three rectifiers are connected in a stacked topology. The simulated and measured results demonstrate that the circuit operates well in concurrent bands. Moreover, the proposed circuit exhibits a low-complexity structure and compactness in size. These advantages make the circuit a strong potential candidate for running low-power devices in IoT sensor networks.

Keywords: RFEH, Antenna, Rectifier, Triple-band

1. Introduction

In the era of the 4th industrial revolution, the number of smart-radio devices is increasing remarkably, especially the number of wireless sensors used in wireless sensor networks; smart devices in IoT networks; body-mounted, wearable radio devices, and wireless sensors for monitoring drought, natural disasters, traffic sensors, etc. They are all low-power radio devices that are deployed with high density in the networks. One of the most critical requirements for these smart devices is the ability to remain in uninterrupted operation over long periods. This is because these radio devices are deployed in complex locations, such as inside the human body; in remote and inaccessible areas, such as riverbeds; in complex terrains, such as offshore seas and islands; or in the mountains, where access to electrical power sources or the replacement of DC power sources such as batteries is impossible or complicated. Besides, the DC battery has a certain lifespan, and replacement cannot be made immediately or when facing stringent challenges if the devices are deployed in hard-to-reach and remote locations or inside the human body. In terms of the environment, a battery is a chemical source that can be harmful. Hence, finding new sources of renewable energy, or alternative green energy sources, helps to protect the environment. These reasons have led to the emergence of research on renewable energy sources for running these sensor devices without the need for a battery. Recently, there has been research into energy harvesting techniques from various sources in the environment, including thermal energy [1, 2], solar energy [3, 4], and mechanical energy [5]. However, these energy sources depend largely on the weather, and they are not continuous. Although solar energy provides high power levels, it is only available when the sun is up. Wind power is difficult for body-mounted radio devices to access, and wind is not continuous or stable. Heat energy and oscillation power are small and not continuous. The biggest drawback to these renewable energy sources is the discontinuity. In addition to these sources, radio frequency (RF) energy has recently become a promising renewable energy source due to the increasing number of wireless signal sources in the environment, including mobile base stations [6], Wi-Fi [7], radio and television transmitters [8-10], Bluetooth, laptops, and mobile phones [11-14]. These RF energy sources are not only continuous but highly condensed in the environment. These superior advantages make this type of

Luong Duy Manh, Phan Thi Bich, Nguyen Thuy Linh, Nguyen Huy Hoang, Xuan Nam Tran and Koichiro Ishibashi, "A Concurrent Triple-band RF Energy Harvesting Circuit for IoT Sensor Networks ," *IEEK Transactions on Smart Processing and Computing*, vol.10, no.20, April 2021.



An Energy Efficient, Long Range Sensor System for Real-Time Environment Monitoring

Van-Phuc Hoang, Van-Lan Dao, Van-Trung Nguyen, Xuan Nam Tran, and Koichiro Ishibashi

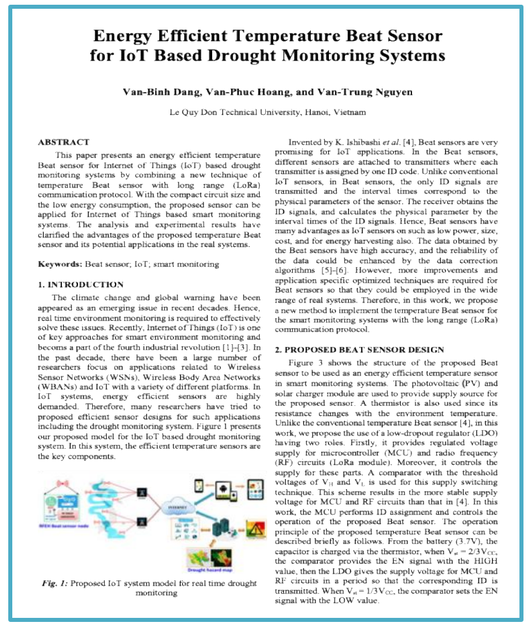
Abstract Vietnam is among the top countries in the world at risk of natural hazards so that efficient real-time environment monitoring is becoming essential. The continuous development in information and communication technology is inspiring the development of the smart monitoring systems for environmental management and protection. This paper presents an energy efficient, long range sensor system for Internet of Things (IoT)-based smart environment monitoring and early warning. The proposed system combines the novel energy efficient temperature. Beat sensors integrated with the LoRaWAN communication protocol and web interface. The experimental results are achieved to clarify the efficiency of the proposed sensor system and its potential applications in the real systems.

Keywords Beat sensor · Drought monitoring · Internet of things

1 Introduction

Vietnam is among the top countries in the world at risk of water-related threats including drought, flood, storm, coastal and agriculture hazards. Among water-related disasters, droughts are highly complex, frequently occurring natural hazards in Southeast Asia including Vietnam [1]. Droughts severely impact on the economy and directly affect infrastructure, properties and people in large geographical regions for extended periods. Due to the characteristics of drought, real-time measuring and monitoring of full impacts of drought are complicated; hence, it requires research, extensive data and experiential evidences for decision-making processes. This leads

VP. Hoang, VL. Dao, VT. Nguyen, X.N. Tran, K. Ishibashi, "An Energy Efficient, Long Range Sensor System for Real-Time Environment Monitoring," *Lecture Notes on Data Engineering and Communications Technologies*, vol. 141, Springer, 2022.



Energy Efficient Temperature Beat Sensor for IoT Based Drought Monitoring Systems

Van-Binh Dang, Van-Phuc Hoang, and Van-Trung Nguyen

Le Quy Don Technical University, Hanoi, Vietnam

ABSTRACT

This paper presents an energy efficient temperature Beat sensor for Internet of Things (IoT) based drought monitoring systems by combining a new technique of temperature Beat sensor with long range (LoRa) communication protocol. With the compact circuit size and the low energy consumption, the proposed sensor can be applied for Internet of Things based smart monitoring systems. The analysis and experimental results have clarified the advantages of the proposed temperature Beat sensor and its potential applications in the real systems.

Keywords: Beat sensor; IoT; smart monitoring

1. INTRODUCTION

The climate change and global warning have been appeared as an emerging issue in recent decades. Hence, real time environment monitoring is required to effectively solve these issues. Recently, Internet of Things (IoT) is one of key approaches for smart environment monitoring and becoms a part of the fourth industrial revolution [1]-[3]. In the past decade, there have been a large number of researchers focus on applications related to Wireless Sensor Networks (WSNs), Wireless Body Area Networks (WBANs) and IoT with a variety of different platforms. In IoT systems, energy efficient sensors are highly demanded. Therefore, many researchers have tried to proposed efficient sensor designs for such applications including the drought monitoring system. Figure 1 presents our proposed model for the IoT based drought monitoring system. In this system, the efficient temperature sensors are the key components.

Fig. 1: Proposed IoT system model for real time drought monitoring

Invented by K. Ishibashi *et al.* [4], Beat sensors are very promising for IoT applications. In the Beat sensors, different sensors are attached to transmitters where each transmitter is assigned by one ID code. Unlike conventional IoT sensors, in Beat sensors, the only ID signals are transmitted and the interval times correspond to the physical parameters of the sensor. The receiver obtains the ID signals, and calculates the physical parameter by the interval times of the ID signals. Hence, Beat sensors have many advantages as IoT sensors on such as low power, size, cost, and for energy harvesting also. The data obtained by the Beat sensors have high accuracy, and the reliability of the data could be enhanced by the data correction algorithms [5]-[6]. However, more improvements and application specific optimized techniques are required for Beat sensors so that they could be employed in the wide range of real systems. Therefore, in this work, we propose a new method to implement the temperature Beat sensor for the smart monitoring systems with the long range (LoRa) communication protocol.

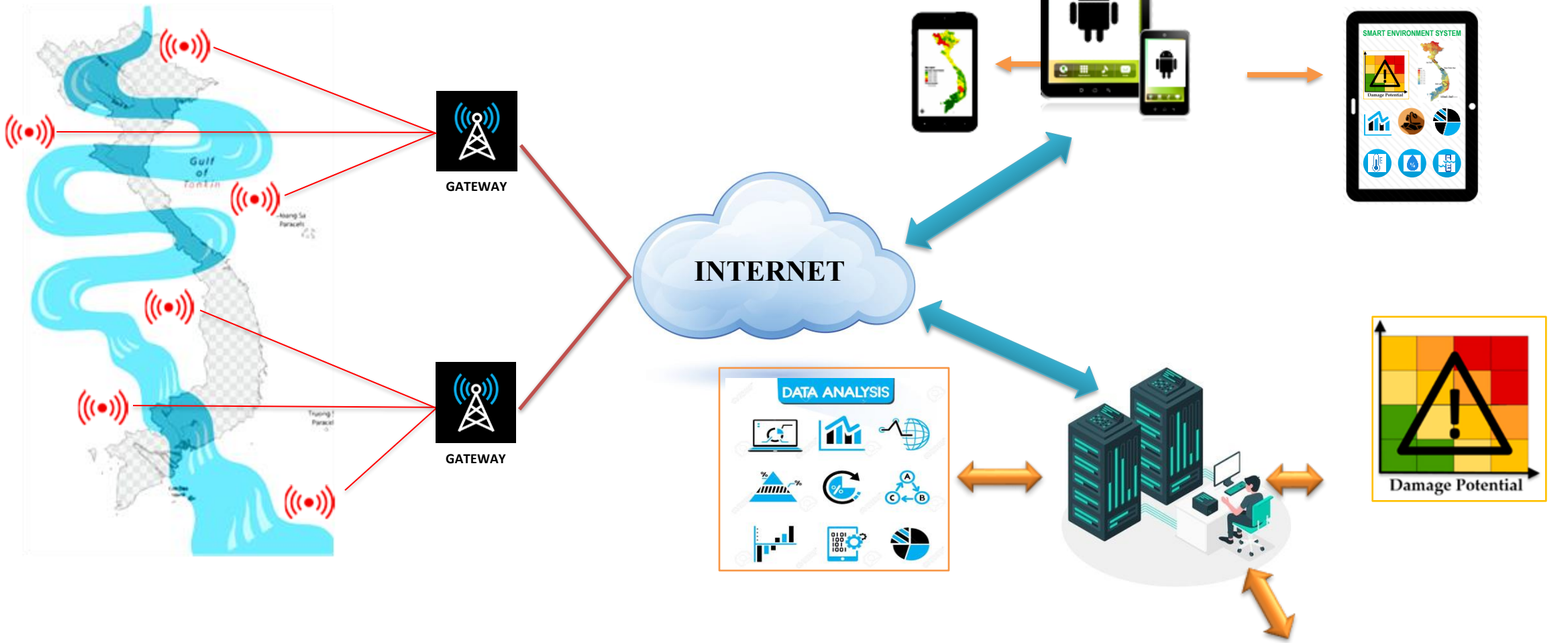
2. PROPOSED BEAT SENSOR DESIGN

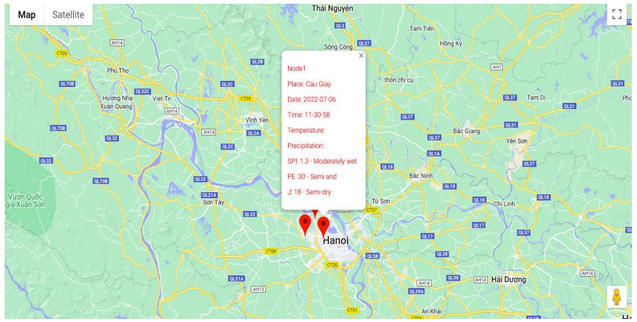
Figure 3 shows the structure of the proposed Beat sensor to be used as an energy efficient temperature sensor in smart monitoring systems. The photovoltaic (PV) and solar charger module are used to provide supply source for the proposed sensor. A thermistor is also used since its resistance changes with the environment temperature. Unlike the conventional temperature Beat sensor [4], in this work, we propose the use of a low-dropout regulator (LDO) having two roles. Firstly, it provides regulated voltage supply for microcontroller (MCU) and radio frequency (RF) circuits (LoRa module). Moreover, it controls the supply for these parts. A comparator with the threshold voltages of V_H and V_L is used for this supply switching technique. This scheme results in the more stable supply voltage for MCU and RF circuits than that in [4]. In this work, the MCU performs ID assignment and controls the operation of the proposed Beat sensor. The operation principle of the proposed temperature Beat sensor can be described briefly as follows. From the battery (3.7V), the capacitor is charged via the thermistor, when $V_{in} = 2/3V_{CC}$, the comparator provides the EN signal with the HIGH value, then the LDO gives the supply voltage for MCU and RF circuits in a period so that the corresponding ID is transmitted. When $V_{in} = 1/3V_{CC}$, the comparator sets the EN signal with the LOW value.

Van-Trung Nguyen et al., "High-Efficient DC-DC Converter Based on Hybrid SI-SC Topology for Portable Devices," *2022 International Conference on IC Design and Technology (ICICDT)*, 2022, pp. 36-39.

Project Outcomes

Prototype System Implementation





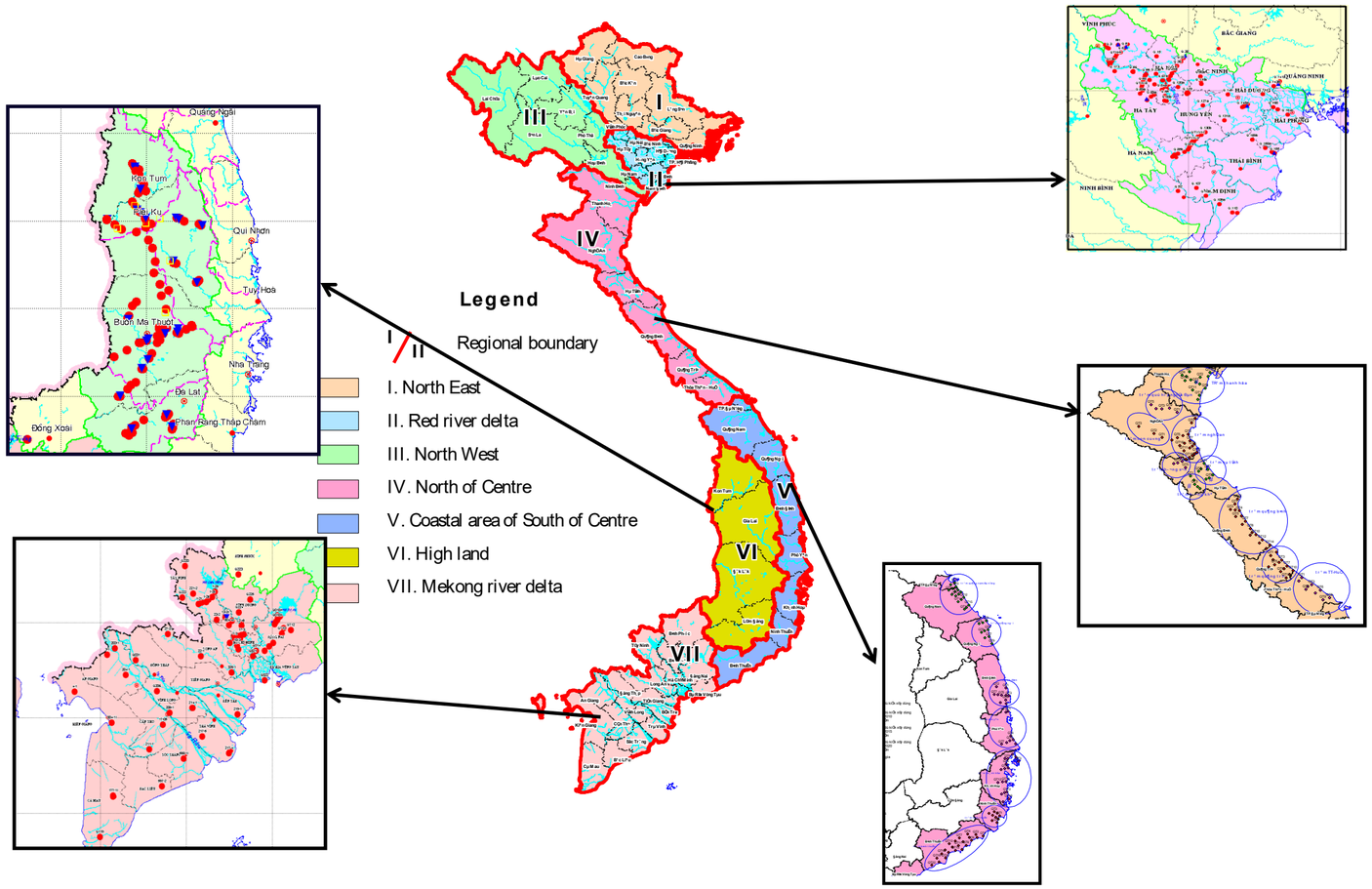
KEY BENEFITS

- Continuous monitoring water level, temperature, humidity.
- Display sensing information on monitoring computer.
- Provide warning for extreme conditions

Post Project Activities

Further Deployment of Test-bed

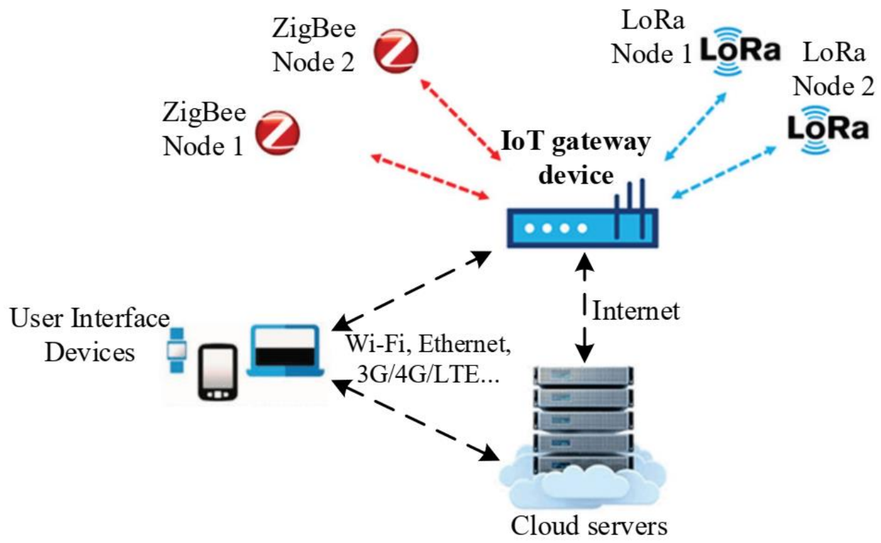
- Plan to extend of test-bed system to build a nationwide water resource monitoring system
- Total: Expected 731 monitoring wells

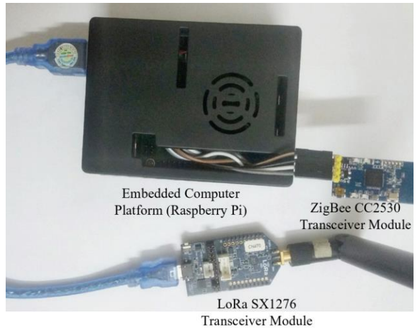


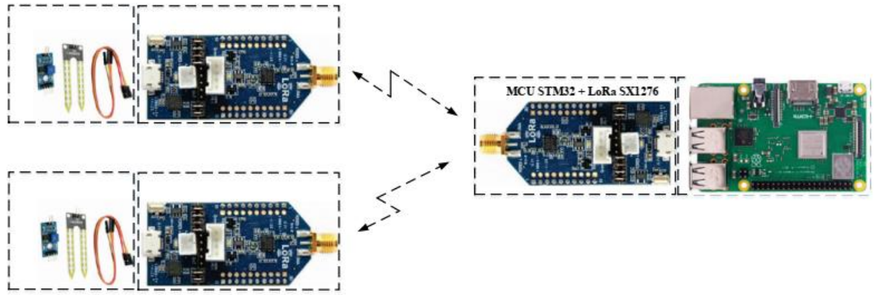
Post Project Activities

Further Deployment of Test-bed

- Build IoT gateway for environment monitoring by combining multiple communication protocols (LoRa, Wi-Fi, Zigbee, 4G/LTE).
- Add tiny ML functions for lightweight AI applications.



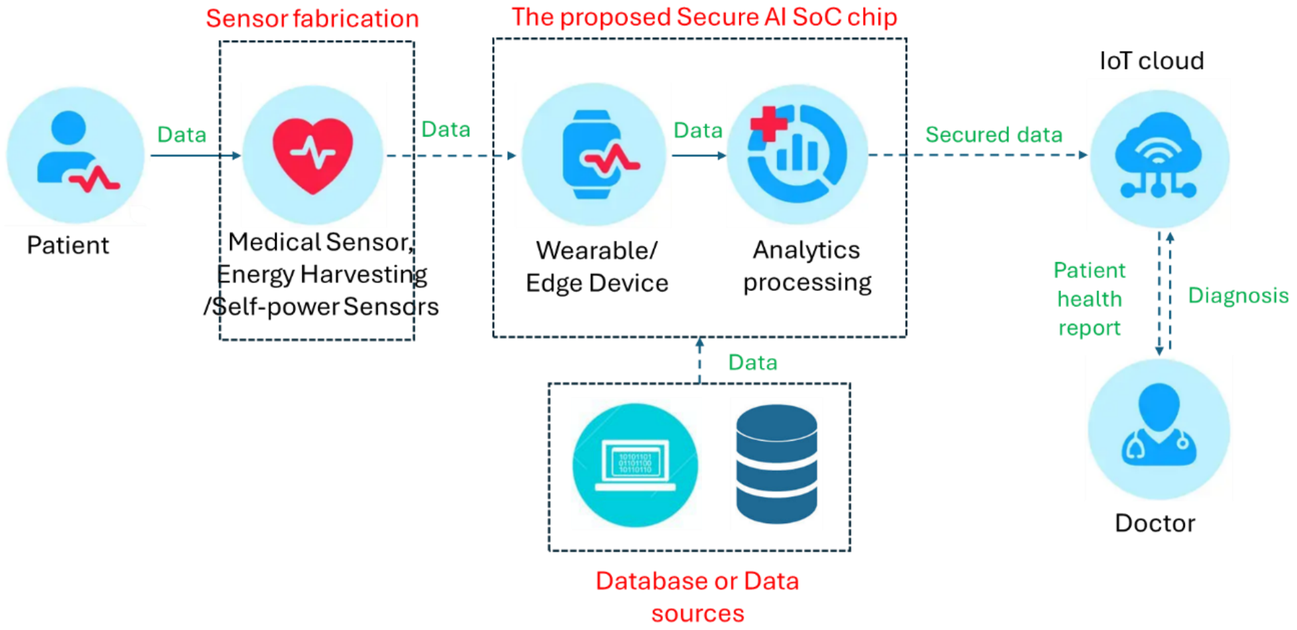




Post Project Activities

Extension to AI-IoMT Applications

- To fabricate medical sensors with energy harvesting/Self-power sensors for Internet of Medical Things (IoMT) applications.
- To fabricate secure AI System-on-Chip (SoC) chip for IoMT.
- Japan-Vietnam collaborate project (NEXUS) on semiconductor



NEXUS 日 ASEAN 科学技術・イノベーション協働連携事業
Networked Exchange, United Strength for Stronger Partnerships between Japan and ASEAN

国立大学法人 電気通信大学 The University of Electro-Communications

東北大学 TOHOKU UNIVERSITY

LE QUY DON Technical University

HCMUS Viet Nam National University Ho Chi Minh City University of Science

Ho Chi Minh City University of Technology

- Project "*Implementation of Secure AI System-on-Chip based on Multi-core RISC-V CPU and AI Accelerator for AI-IoMT devices and Applications*" funded The Japan Science and Technology Agency (JST) and the Vietnam Ministry of Science and Technology (MOST).
- Duration: 10/2025 – 3/2029

Conclusion and Future Outlook

Conclusions

- Successfully developed and field-tested an IoT-based drought monitoring and early warning system.
- Demonstrated long-range, energy-efficient, and self-sustainable sensor operations.
- Produced significant academic outcomes: SCIE/Scopus journal papers, international conference presentations, and technical reports.
- The project was sponsored by ASEAN IVO and greatly benefited from strong collaborations with international and local research partners.

Future Outlook

- Scale up into a nationwide water resource monitoring system.
- Integrate multi-protocol gateways with lightweight AI for intelligent monitoring and decision-making.
- Extend applications towards healthcare and IoMT through international collaborations.
- Continue fostering research partnerships to leverage complementary expertise and ensure impactful outcomes.

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- Gratitude to the project team members for their dedication and contributions to both academic and practical outcomes.

Thank you for your attention.

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