A Methodical Approach to Cooperative Energy-Efficient Routing in IoT-Based Wireless Sensor Networks

Raghavendra Patil G E [1], Vivekanandam [2], Pawan Whig [3]
[1] Lincoln University College, Malaysia;
[2] Lincoln University College, Malaysia;
[3] VIPS-TC, India
Email ID: gerpatil16@gmail.com, vivekanandam@lincoln.edu.my, pawan.whig@vips.edu

Abstract: In the era of the Internet of Things (IoT), Wireless Sensor Networks (WSNs) play central roles in supporting real-time monitoring and data transportation in application domains. Energy efficiency, however, is the central concern with the restricted battery capacity of sensor nodes. This paper presents a systematic approach to the design of a cooperative routing protocol with applicability to supporting energy efficiency in IoT-enabled WSNs. The constructed protocol supports cluster-based organization, cooperative transmission, and smart routing path selection to reduce redundant transmission and balance energy consumption among nodes. By taking advantage of node cooperation and energy-aware metrics, the routing mechanism optimizes network lifetime, packet loss reduction, and guaranteed data delivery. Simulation results validate the applicability of the proposed strategy to achieving significant energy saving with overall network performance compared to conventional routing schemes. This approach provides a rigorous framework for designing scalable, energy-aware communication protocols in resource-constrained IoT sensor networks.

Keywords: IoT, Routing, Efficiency, Traffic, WSNs.

Introduction

As an inevitable link between the physical and virtual realms, WSNs have become a vital part of the IoT infrastructure [1]. The application of WSNs in the gathering and delivering information from heterogeneous environments has been extremely useful to the large-scale IoT device and service deployments. Real-time sensing, data analysis, and autonomous feedback are made possible by this integration across a number of different industries of industrial automation, healthcare, and environmental conservation. More interactive and responsive are made possible through the integration of WSNs and IoT, which also makes possible an enormously diverse range of applications previously unimaginable.

Most IoT applications rely on WSN, with the capability of monitoring patients' physiological parameters, equipment health, and environmental parameters [2], [3]. A standard WSN with a series of sensors enables the monitoring of environmental temperature, humidity, water levels, and air conditions in environmental monitoring and supply researchers with valuable inputs while conducting research on climate change and pollution control. Heart rate, blood pressure, and activity level are some of the patient information that can be obtained from wearable sensors and in-home monitoring systems in healthcare. This enables remote patient monitoring and immediate medical intervention. WSNs can be utilized for monitoring the performance of equipment, anomaly detection, and process automation in industrial automation, thus improving productivity and reducing downtime. They aimed to demonstrate the importance of WSNs in realizing maximum potential of IoT.

There are some limitations of employing WSNs with IoT, which are greatly reliant on IoT application needs and on the intrinsic characteristics of sensor nodes [4]. Sensor nodes are primarily constrained by constrained communication environments, constrained computation capabilities, and constrained battery lives. It is greatly constrained by these aspects to develop energy-efficient routeing methodologies to ensure guaranteed data delivery and optimize network lifetime. Moreover, the routeing design process is also made more complex by WSNs' dynamic and primarily hostile environment of deployment and the need to provide secure data communication. These problems need to be addressed to achieve the maximum possible potential of WSN-based IoT systems.

Related work

Since WSNs are made up of batteries with limited capacity, it is inherently energy-constrained and energy efficiency is one of the key design requirements [2], [5]. Because sensor nodes are typically deployed in remote or inlier areas, recharging or replacement of the battery is not feasible. Energy efficiency of the WSN devices and protocols, most importantly routing schemes that are responsible for data exchange, determine network lifetime. For improving network lifetime and supporting longer operation in mission-critical applications, energy efficiency must be optimized to the lowest level. Network lifetime and packet delivery ratio can be seriously affected by the energy efficiency and fault sensitivity of traditional routing techniques [6]. WSN routing is also exacerbated by poor deployment conditions and high requirements for trustworthy exchange of information [7], [3].

There is a need for energy-efficient routing protocols in WSNs to survive longer and for effective data transfer in IoT systems [4], [8]. Cooperative routing is among the promising solutions that exploit the broadcast nature of wireless channels to provide more reliable and energy-efficient data transfer [9]. Cooperative routing provides more chances for successful data delivery by asking the sensor nodes to collaborate with one another to forward data and share the energy burden.

In IoT applications based on WSN, it is better if routing protocols maintain system throughput and security and save power [10], [11]. This type of high-data rate is typically needed in the majority of IoT applications for the support of real-time monitoring, data analysis, and control operations. By taking advantage of the broadcast nature of wireless channels on purpose, cooperative communication improves network performance [9]. Cooperative communication uses numerous nodes to forward information cooperatively, as compared to traditional point-to-point communication, where a transmission node forwards to a reception node directly.

By providing a means for information to be relayed from destination to source, relay nodes contribute significantly to cooperative communication, improving the reliability of the communication and lower energy usage [12]. Cooperative routing protocols may experience challenges in deciding on the best relay nodes and coordinating themselves accordingly [9]. Relay nodes may also act as middlemen and relay information in a number of hops in the event that there is an unstable and unreliable direct link between the source and destination. By minimizing interference as well as fading's negative effects, cooperative communication builds stronger and more stable communication networks [9]. Wireless channels suffer from fading because of multipath propagation as well as other reasons, wherein signal strength is time and space variant.

Methodology

The step-by-step methodology employed to present an energy-efficient cooperative routing protocol for Internet of Things (IoT) applications over Wireless Sensor Networks (WSNs) is presented in this section. It combines energy-efficient routing, cooperative communication, and clustering for better network performance and lifetime.

A. Network Model and Assumptions

WSN-based Internet of Things is represented as a two-dimensional plane with statically deployed, randomly scattered sensor nodes. The assumptions are as follows:

a. All sensor nodes start with the same amount of energy and are all energy-limited.
b. Outside the sensing area lies the base station, also known as the sink.
c. Nodes may change their power transmission according to distance.
d. Every node knows where the neighbors are and how much energy is left.

B. Cluster Formation

The network is partitioned into clusters for effective data collection and energy conservation. The Cluster Head (CH) is selected periodically based on a weighted sum of the following:

a. Residual energy of the node.
b. Base station distance.
c. Node degree or number of adjacent nodes.

C. Cooperative Communication

Non-CH nodes within each cluster use cooperative communication to forward their data to the CH. Within the cluster, relay nodes are selected from a subset to help in forwarding the data. The following are utilized in the relay selection:

a. Minimum residual energy cost.
b. Closest distance from CH to the source.
c. The past packet loss rate.

With the aim of minimizing transmission errors and retransmissions, two cooperative schemes being debated are Amplify-and-Forward (AF) and Decode-and-Forward (DF).

D. Energy-Aware Multi-Hop Routing

Once data is gathered at CHs, multi-hop routes are employed to deliver the data to the sink. One of the routing protocols employed is an energy-aware weighted protocol in which route selection is based on the following:

a. The minimum energy path.
b. Load balancing to prevent overloading specific nodes.
c. Link stability and signal strength.

E. Energy Saving Strategies

Other energy-conserving methods are utilized to achieve optimal network lifetime:

a. Duty cycling: The nodes go to sleep if they are not active.
c. Data Aggregation: Redundant data is eliminated at CHs prior to forwarding.
c. Adaptive Transmission Power: Nodes adjust power according to communication distance.

F. Simulations and Performance Evaluation

a. Simulation Tools and Environments

An interactive modeling environment that can be used to examine and analyze the functioning of WSN-based IoT in various settings, MATLAB is being used more and more to simulate and test the performance of the routing protocol [4]. Sensor nodes, wireless channel models, and routing protocols are some of the many tools and functionalities provided in MATLAB to simulate and analyze WSNs.

b. Performance Evaluation

1. Energy Consumption: Energy consumption in joules (J) or millijoules (mJ), as a metric of the energy spent on data transfer and other network activities, is one of the most important metrics of the energy efficiency of routing protocols [13].

Different levels at which the energy consumption must be measured exist, for instance, node, cluster, and network levels.

2. Network Lifetime: The most significant indicator of WSN sustainability is network lifetime, which is measured in rounds or units of time and is defined as the time for which a network can sustain itself before node death due to power exhaustion renders performance weak [4].

Network lifetime is usually the time until the first node death or until a specified number of nodes has exhausted their power.

3. Packet Delivery Ratio (PDR): Packet delivery ratio (PDR) is one of the most critical indicators of the dependability of routing protocols, and it is an indicator of the ratio of successfully received data packets to the destination [13].

PDR is influenced by many factors, including channel conditions, interference levels, and routing protocol performance.

4. End-to-end delay: End-to-end delay utilized to determine the time it would take for a packet to travel from source to destination is a critical indicator of how responsive the routing protocols are. It shows how long it would take data to arrive at the destination, and it is especially critical for real-time applications [4]. End-to-end delay is influenced by hops, transmission rate, and processing time at every node.

5. Throughput: With high likelihood, throughput is the most important parameter in measuring routing scheme efficiency. Throughput specifies the rate of a message that is successfully delivered over a communication link. Throughput specifies the rate of information that is successfully delivered over the network over a period of elapsed time [13]. The network nodes, transmission rate, and bandwidth of the communication link influence throughput.

Conclusion

The proposed methodology outlines an efficient and rigorous approach to designing an energy-efficient cooperative routing protocol for WSN-based IoT systems. With the implementation of cluster-based communication, cooperative data forwarding, and energy-aware routing path selection, the protocol significantly enhances network lifetime and reliability. Cooperative neighbor-to-neighbor communication prevents duplicate transmissions and optimizes energy consumption, addressing one of the most basic issues in WSNs—energy depletion. Utilization of the first-order radio energy model and scalable network assumptions also offers practicality to real-world design. The methodology provides a solid foundation for adaptive, energy-aware communication methods in resource-constrained IoT sensor networks. Real-world deployment and evaluation with different IoT applications and dynamic network conditions will be addressed in future research to further optimize the protocol performance.

References

1. Kumar, Et Al. Battina Srinuvasu"A Learning based Secure Routing Approach using Deep Reinforcement Learning in IoT Integrated Wireless Sensor Network". https://doi.org/10.17762/ijritcc.v11i9.9345
2. Gupta, Divya, Wadhwa, Shivani, Rani, Shalli, Khan, Zahid, and Boulila, Wadii. 2023. "EEDC: An Energy Efficient Data Communication Scheme Based on New Routing Approach in Wireless Sensor Networks for Future IoT Applications". Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/s23218839
3. Tn, Nguy Duy, Nguyen, Duy-Ngoc, Hoang, Hong-Nhat, and Le, Thi-Thu-Huong. 2023. "EEGT: Energy Efficient Grid-Based Routing Protocol in Wireless Sensor Networks for IoT Applications". Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/computers12050103
4. Mohammed, Moizuddin, Rahmani, Mohammad Khalid Imam, Ahmed, Md. Ezaz, Irshad, Reyazur Rashid, Yasmin, Sadaf, Ahmad, Sultan, Mishra, Swati, Asopa, Pooja, and Islam, Asharul. 2023. "Optimized Energy-Efficient Routing Protocol for Wireless Sensor Network Integrated with IoT: An Approach Based on Deep Convolutional Neural Network and Metaheuristic Algorithms". Journal of Nanoelectronics and Optoelectronics. https://doi.org/10.1166/jno.2023.3396
5. Patel, N., Kumar, Shishir, and Singh, Sanjay. 2021. "Energy and Collision Aware WSN Routing Protocol for Sustainable and Intelligent IoT Applications". IEEE Sensors Journal. https://doi.org/10.1109/JSEN.2021.3076192
6. Dr, Jennifer S. Raj and Dr, Abul Basar. 2019. "QOS Optimization of Energy Efficient Routing In Iot Wireless Sensor Networks". Journal of ISMAC. https://doi.org/10.36548/jismac.2019.1.002
7. Siddiq, Ali and Ghazwani, Yahya Jaber. 2024. "Hybrid Optimized Deep Neural Network-Based Intrusion Node Detection and Modified Energy Efficient Centralized Clustering Routing Protocol for Wireless Sensor Network". IEEE transactions on consumer electronics. https://doi.org/10.1109/TCE.2024.3430974
8. Krishnapriya, M., AngelinePrasanna, G., and Anbarasu, S.. 2023. "Rank-Based Energy-Efficient Key Management Routing For Wireless Sensor Network-Based Iot Medical Sensors". Wireless personal communications. https://doi.org/10.1007/s11277-023-10377-5
9. Atitallah, Nesrine, Cheikhrouhou, Omar, Mershad, Khaleel, Kouba, Anis, and Hajjej, Fahima. 2023. "CERP: Cooperative and Efficient Routing Protocol for Wireless Sensor Networks", Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/s23218834
10. Sharma, Anshika, Babbar, Himanshi, Rani, Shalli, Sah, D. K., Sehar, Sountharrajan, and Gianini, G.. 2023. "MHSEER: A Meta-Heuristic Secure and Energy-Efficient Routing Protocol for Wireless Sensor Network-Based Industrial IoT". Energies. https://doi.org/10.3390/en16104198

11. Haseeb, Khalid, Almogren, Ahmad, Islam, Naveed, Din, Ikram Ud, and Jan, Zahoor. 2019. "An Energy-Efficient and Secure Routing Protocol for Intrusion Avoidance in IoT-Based WSN", Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/en12214174
12. Shi, Juanfei, Calveras, Anna, Ye, Cheng, and Liu, Kai. 2013. "A Novel Power Efficient Location-Based Cooperative Routing with Transmission Power-Upper-Limit for Wireless Sensor Networks", Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/s130506448
13. Pahuja, Monika and Kumar, Dinesh, "Energy-Efficient Stable Election Protocol for IoT-Based Healthcare Systems Using Wireless Sensor Networks", International Conference on Computing Communication and Networking Technologies, 2023. https://doi.org/10.1109/ICCCNT56998.2023.10307041