EVALUATION OF DATA COLLECTION TREE ROUTING PROTOCOLS FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

In recent years, wireless sensor networks (WSNs) have garnered significant research attention due to their versatility in supporting a range of applications, including military surveillance, environmental monitoring, and infrastructure protection. WSNs offer low deployment costs, low energy consumption, and adaptability to complex geographical and climatic conditions. Particularly notable are their capabilities for self-organization, collaborative processing, and fault tolerance, which open up promising application potential across various fields. This paper focuses on the simulation and evaluation of data collection routing protocols in WSNs, specifically the Collection Tree Protocol (CTP) in mobile environments using the Contiki operating system and the Cooja simulator. Applications of data collection routing protocols in mobile environments include military surveillance and livestock monitoring. This study addresses efficiency issues such as energy savings and the maintenance of high data packet delivery rates under mobile network node conditions. These contributions provide practical benefits for both society and scientific advancement.

Keywords: CTP protocol; routing in WSN; WSN energy-saving solutions; WSN performance; CTP in mobile environments.

1. Introduction

A Wireless Sensor Network (WSN) is an infrastructure that combines sensing (measuring), computing, and communication components to enable administrators to measure, observe, and respond to events and phenomena within a specific environment. Typical applications of WSNs include data collection, tracking, surveillance, and healthcare [1], [2].

A WSN consists of numerous network nodes. These nodes are typically simple, compact, low-cost devices, widely available, and often distributed over large areas. They rely on limited energy sources (usually batteries) and have constrained operational lifetimes. WSNs are designed for long-term operation - often lasting from several months to years - and can function in harsh environments (e.g., toxic or polluted areas, high-temperature conditions) [3], [4]. Routing in sensor networks occurs at the network layer, with sensor nodes densely distributed in fields near or adjacent to each other. An efficient centralized data routing protocol is essential to facilitate data transfer between sensor nodes and the receiver [5].

In a sensor network, each node acts as both a source and a data relay. The failure of several nodes may lead to network topology changes, packet rerouting, and network reorganization. Therefore, developing and refining routing protocols for WSNs is crucial. Due to these factors, many researchers have focused on designing algorithms and protocols to optimize sensing and energy consumption in sensor networks [6], [7], [8].

This article presents the results of simulating the CTP (Collection Tree Protocol) routing protocol in a WSN environment using Cooja software. Simulated scenarios with an increasing number of network nodes were analyzed to evaluate the average energy consumption rate, data message delivery rate, and overall network stability. Additionally, potential applications of data collection tree protocols for WSNs are proposed.

2. Operational mechanism and network traffic

2.1. Wireless Sensor Network architecture

The basic architecture of a wireless sensor network is illustrated in Figure 1. Sensor nodes are deployed across a sensor field, each with the capability to collect data, route it to the receiver for user access, and forward messages based on requests from the Sink node to other sensor nodes. Data is transmitted toward the receiver (Sink) using a Multihop Infrastructureless Architecture, meaning no base transceiver stations or control centers are required. The receiver can communicate directly with the user's operating station (Task Manager Node) or indirectly via the Internet or satellite [1], [2].

Network nodes communicate through an ad hoc radio network, transmitting data to the Sink using multi-hop technology. The Sink can then communicate with end users or managers via the Internet, satellite, or other wireless networks, such as WiFi, cellular networks, or WiMAX, and may also connect directly without network support. The architecture in Figure 1 allows for multiple Sinks/Gateways and multiple end users.

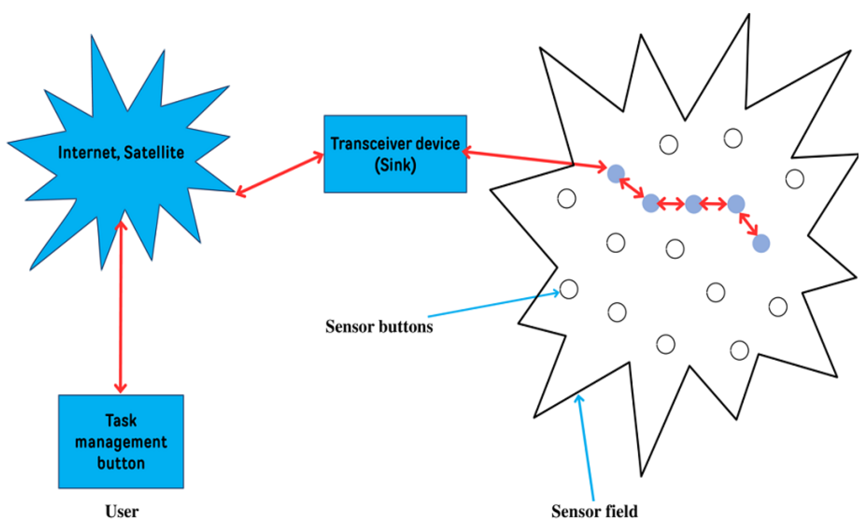

Figure 1: *Architecture of Wireless Sensor Network and sensor nodes scattered in the sensor field*

In wireless sensor networks, sensor nodes function both as data originators and data routers. Communication can be performed in two main roles:

1. **Data source function:** Nodes collect information on events and send their data to the Sink.

2. **Router function:** Sensor nodes also forward packets received from other nodes to the next destination in the multi-hop route to the Sink.

Typically, a sensor node consists of two primary components: a sensor probe and an analog/digital converter. Most routing techniques in sensor networks require precise location awareness. Therefore, sensor nodes often need a navigation system to position themselves accurately and carry out assigned tasks within the network [3].

2.2. Communication stack and MAC protocol in wireless sensor networks

Communication stack for Wireless Sensor Networks

The protocol stack architecture, illustrated in Figure 2, combines energy-efficient routing, data aggregation protocols, and low-power communication over a wireless medium. This protocol stack architecture consists of five layers: the physical layer, data link layer, network layer, transport layer, and application layer. Additionally, it includes multiple management planes: the synchronization plane, location plane, topology management plane, power management plane, mobility management plane, and mission management plane.

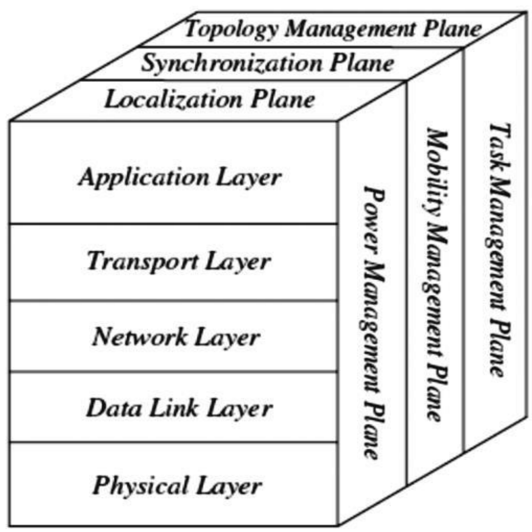

Figure 2: *Wireless sensor network protocol stack architecture*

MAC protocol in Wireless Sensor Networks

The Medium Access Control (MAC) protocol in a multi-hop, self-organizing sensor network must achieve two primary objectives. The first objective is to establish a robust network infrastructure. The second objective is to efficiently allocate communication resources - such as time, energy, and frequency - among sensor nodes. For any channel access mechanism, energy efficiency is paramount. Therefore, a MAC protocol must support energy-saving operation modes for the sensor nodes to maximize their operational lifespan.

2.3. CTP data collection tree protocol

One of the most effective data collection protocols for wireless sensor networks is the CTP (Collection Tree Protocol), illustrated in Figure 3. CTP is built on a flat, self-organizing routing approach, allowing efficient communication from network nodes in the sensor field to a designated root node [4].

All data collection protocols facilitate packet forwarding to a data collection point (Sink/Gateway) using a routing tree with minimal overhead. The transmission cost is typically calculated as the expected number of ETX (Expected Transmission Count) transmissions, ensuring that nodes send data along the route requiring the fewest transmissions to reach the collection point.

The CTP protocol employs a hop-by-hop, reliable data collection mechanism. Nodes self-organize into a tree structure, and data is relayed to each node's parent until it reaches the top of the tree (the root node). Node 25 is designated as the root, while all other nodes initialize as leaf nodes. Nodes update their positions within the tree structure, which expands progressively from the root node. Data is transmitted through this tree structure to reach the root node [5].

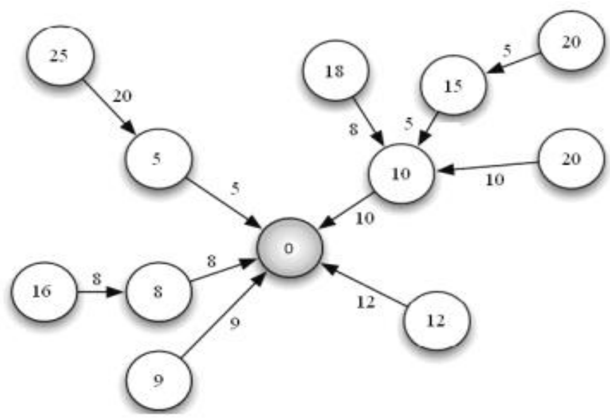

Figure 3: *Network topology built according to the CTP protocol*

2.4. Routing metrics used in the CTP protocol

In the CTP protocol, the routing metric used is the expected number of transmissions, or ETX (Expected Transmission Count). The ETX of a link represents the number of transmissions required to successfully send a message from the source to the destination over that link, including retransmissions. Figure 4 illustrates the calculation of the ETX_{link} metric for a link [5].

Figure 4: *Expected Transmission Count of a link*

The ETX_{link} value is determined by the following formula: $ETX_{link} = \frac{1}{D_f \, D_b}$, where D_f is the message delivery rate in the forward direction from node A to node B; D_b is the message delivery rate in the reverse direction from node B to A.

The link quality of a route, known as the routing metric ($rtmetric$), is calculated by summing the ETX values of all links on that route. Node positions within the tree are determined by the $rtmetric$ values. The root node at the top of the tree has an $rtmetric$ value of 0, while leaf nodes have higher $rtmetric$ values, increasing with their distance from the root node. A route with a higher $rtmetric$ indicates lower-quality links, while the best route is the one with the smallest $rtmetric$. This route has the fewest expected ETX transmissions to the root node and is therefore the most energy efficient.

3. Experimental simulation and evaluation

3.1. Contiki operating system and Cooja simulation software

Figure 5 depicts the Contiki open-source operating system. Contiki is an open-source OS designed specifically for embedded network systems in general and wireless sensor networks (WSNs) [6].

We selected the Contiki OS for WSN research for three main reasons. First, Contiki is one of the most widely used operating systems within the WSN research community today. Second, Contiki is highly suitable for wireless sensor networks and embedded device networks, making it a popular choice in real-world deployments. Third, Contiki uses the C programming language, which is well-known and widely used [7].

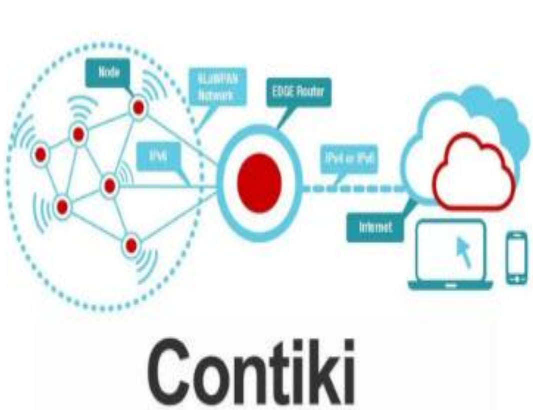

Figure 5: *Contiki open-source operating system [3]*

Figure 6: *Simulation creation interface with Cooja software*

With the interface shown in Figure 6, the combination of Contiki and Cooja enables effective, systematic research, allowing for evaluating critical parameters of the TCP protocol within a WSN environment. Contiki is designed explicitly for sensor networks, optimizing resources such as memory and power. Meanwhile, Cooja allows the simulation of various scenarios, from network configuration to sensor node operations, enabling a comprehensive performance evaluation of the TCP protocol based on metrics like data message delivery and average power consumption. This approach provides a broader assessment compared to previous studies using other software, such as NS2 and Matlab [8].

3.2. Experimental problem

Based on the assumptions illustrated in Figures 7 and 8, the author constructs a cluster model of 26 sensor nodes randomly distributed within a 40 m x 40 m area. Network nodes periodically send data messages to the node designated as root node 26. The effective communication range is 80 m, while the interference range is 100 m. Nodes within the green zone can communicate directly with the root node (node 26), while the remaining nodes must use a multi-hop approach to reach the root node. The MAC layer protocol employed in this simulation is the ContikiMAC protocol.

Number of network nodes (nodes)	26
Network size (m x m)	20m x 40m
Node coverage (m)	Effective transmission range: 80 Interference influence range: 100
Data message sending cycle (seconds)	20
Source sends data message	All nodes in the network (other than node origin)
MAC layer protocol	CSMA/ContikiMAC
Routing type	CTP
Standards of use	IEEE 802.15.4
Simulation time	10 minutes

Figure 7: *Image depicting basic parameters of a cluster model consisting of 26 sensor nodes*

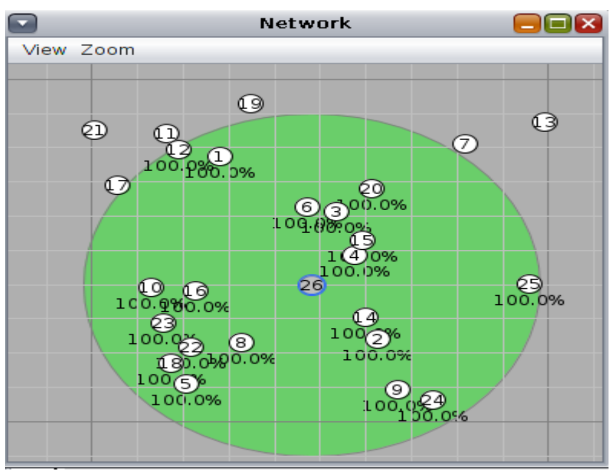

Figure 8: *Scenario for deploying the distribution of sensor nodes in simulation*

The scenario simulates the distribution of sensor nodes, as shown in Figure 7, with the sensor network deployed in a square grid format on a square map. With a network area of 20 m x 40 m and nodes' coverage range, each node can effectively transmit to neighboring nodes within 80 m, while the interference range remains at 100 m. The CTP (Collection Tree Protocol) data collection tree routing protocol is used in this simulation.

3.3. Simulate comments and reviews

Analyzing the simulation results and evaluating the successful data message delivery rate (%), as depicted in Figure 9, shows that the network operates according to the CTP protocol when fixed network nodes achieve higher efficiency than when operating in a mobile environment. However, when network nodes are mobile, we can see a significant difference in the successful delivery rate of data messages. Fixed network nodes will not change locations so that the message delivery rate will be more optimal than in mobile environments.

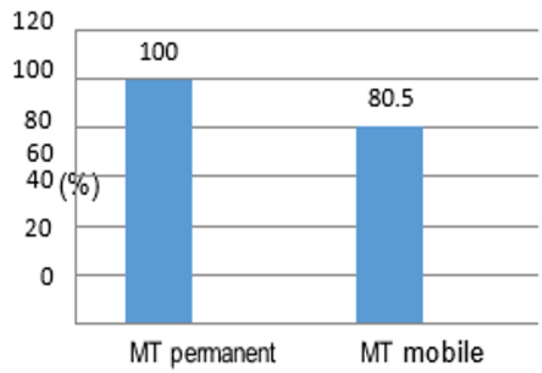

Figure 9: *A comparison of the successful delivery rate of data messages (%) in the network*

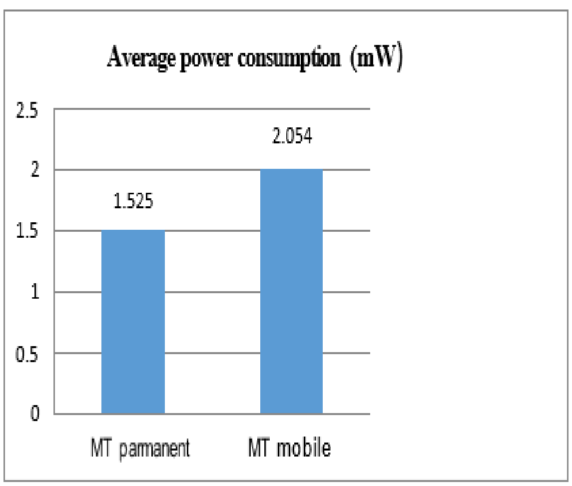

Figure 10: *A comparison of average power consumption in fixed and non-fixed networks*

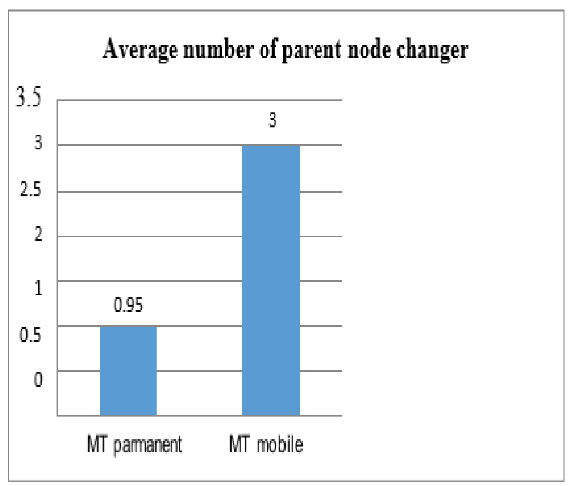

Figure 11: *A comparison when changing the average number of parent nodes in a network*

The graph in Figure 10 shows that the average power consumption in the mobile network consumes more energy than in the fixed environment. The network operates according to the CTP protocol using a retransmission mechanism that allows for achieving high efficiency in data message delivery rates but increases the cost of energy consumption. In a fixed environment, the network operates while ensuring energy savings and achieving relatively good efficiency in the rate of successful delivery of data messages.

Networks operating under the CTP protocol change their topology, as shown in Figure 11. In the case of mobile network nodes, the average number of parent node changes in the network for the CTP protocol increases significantly; as for the fixed environment, there is also a change in the parent node, but it is insignificant. Each time the parent node changes in the network, the nodes must send a control message to notify other nodes to update the network topology. This also increases energy costs for networks operating under the CTP protocol.

4. Conclusion

This article evaluates wireless sensor networks' CTP data collection tree routing protocol. Through experimental simulation, we can see that each fixed or mobile environment will have its own characteristics. However, it will depend on the application we use the CTP protocol in the fixed or mobile environment. Each environment has different advantages and disadvantages, but depending on the application people use, we need to pay attention to saving energy, minimizing costs, etc.

In the article, the author successfully simulated the CTP data collection tree routing protocol on the new simulation tool Cooja, considered one of the most essential simulation tools in IOT research. The article has contributed to solving efficiency issues such as energy saving and a highly successful data message delivery rate in the context of mobile network nodes. This has brought many practical benefits to life and science. The following research direction of the article will focus on solutions to save energy for wireless sensor networks with routing protocols and take advantage of available energy sources in nature.

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TÓM TẮT

NGHIÊN CỨU ĐÁNH GIÁ GIAO THỨC ĐỊNH TUYẾN CÂY THU THẬP DỮ LIỆU CHO MẠNG CẢM BIẾN KHÔNG DÂY

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Ngày nhận bài 04/9/2024, ngày nhận đăng 17/10/2024

Trong vài năm gần đây, mạng cảm biến không dây đã thu hút sự quan tâm lớn trong nghiên cứu nhờ khả năng hỗ trợ đa dạng các ứng dụng, bao gồm giám sát quân sự, giám sát môi trường, và bảo vệ cơ sở hạ tầng với chi phí đầu tư thấp, tiêu thụ ít điện năng, khả năng triển khai trong điều kiện địa hình và khí hậu phức tạp. Đặc biệt, các ưu điểm như khả năng tự tổ chức mạng, khả năng xử lý cộng tác và khả năng chịu lỗi đã tạo nên triển vọng ứng dụng tiềm năng trong nhiều lĩnh vực khác nhau. Bài báo này tập trung vào việc mô phỏng và đánh giá các giao thức định tuyến thu thập dữ liệu trong mạng cảm biến không dây, điển hình là giao thức cây thu thập dữ liệu CTP (Collection Tree Protocol) trong môi trường di động trên hệ điều hành Contiki và phần mềm Cooja. Một số ứng dụng của các giao thức định tuyến thu thập dữ liệu trong môi trường di động bao gồm giám sát quân sự và giám sát vật nuôi. Bài báo góp phần giải quyết các vấn đề liên quan đến tính hiệu quả như tiết kiệm năng lượng và duy trì tỷ lệ chuyển phát thành công cao trong điều kiện các nút mạng di động. Những đóng góp này mang lại nhiều lợi ích thiết thực cho cuộc sống và cho khoa học.

Từ khóa: Giao thức CTP; định tuyến trong WSN; giải pháp tiết kiệm năng lượng WSN; hiệu năng WSN; CTP trong di động.