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Research

Optimizing Energy Efficiency in Wireless Sensor Networks Using Adaptive Routing Algorithms

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Abstract: Wireless Sensor Networks (WSNs) are increasingly deployed in diverse applications such as environmental monitoring, healthcare, and industrial automation. However, the limited energy capacity of sensor nodes presents a significant challenge to the longevity and reliability of these networks. This paper focuses on optimizing energy efficiency in WSNs by implementing adaptive routing algorithms. By dynamically adjusting routing paths based on node energy levels, communication costs, and network topology changes, the proposed adaptive algorithms aim to balance energy consumption across the network and extend its operational lifetime. Simulation results demonstrate that the adaptive routing approach significantly reduces energy depletion, minimizes data transmission delays, and enhances overall network performance compared to traditional static routing methods. The findings highlight the potential of intelligent routing mechanisms in achieving sustainable and energy-efficient WSN operations.

Keywords: Optimizing, Energy Efficiency, Wireless, Sensor, Routing, Algorithms, Wsn

1.0 INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a critical component in modern communication and monitoring systems due to their ability to collect and transmit data from remote or inaccessible environments. These networks consist of spatially distributed sensor nodes that can sense, process, and communicate information wirelessly (Akyildiz et al., 2002). Despite their wide range of applications, including environmental monitoring, military surveillance, industrial automation, and healthcare, one of the primary challenges limiting the efficiency and reliability of WSNs is energy consumption. The wireless Sensor Network blocks is shown in Figure 1.

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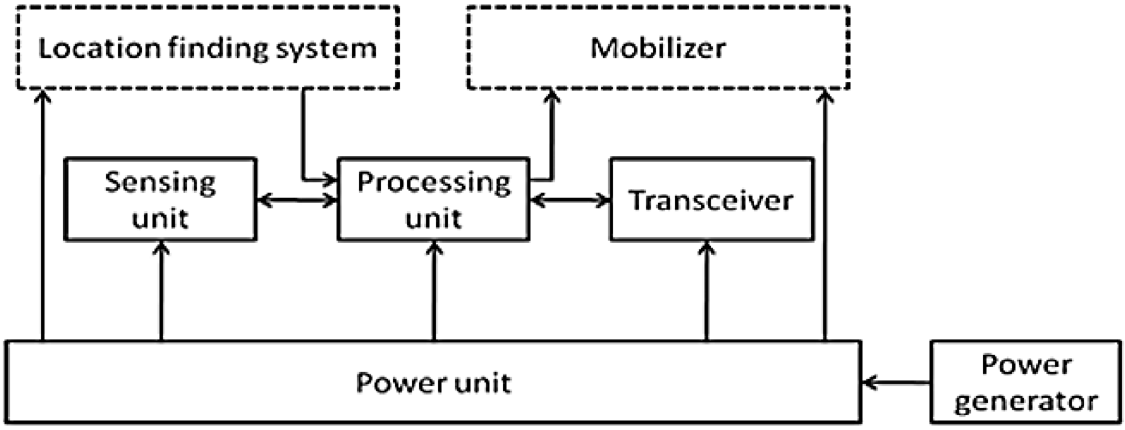

Fig. 1: WSN Components © (Malik, 2013)

Features of WSN include their small size, security architecture, power sources, too many small memories space as in Table 1.1, and low bandwidth (Malik, 2013).

- **Small Size**: There could be hundreds or even thousands of independent nodes in a sensor network. Size is important for a network this size. Because sensors are kept compact, only the most important components are put on the sensor's primary chipboard. Since sensors can be placed so they are invisible, their small size could be seen as a benefit. references (Malik, 2013).
- **Power Sources**: Energy inefficiency in wireless networks results from the non-renewable power resources found in WSN sensors. Because of the network's volume and spread, sensors cannot be recharged, making node recharging a time-consuming and costly process. In WSN, power constraints are thought to be the main factor limiting network performance. Every node requires power since they all do local processing (Malik, 2013).
- **Security Architecture:** Typically, sensors gather environmental data and carry out their assigned tasks. They must deal with exposed environments that could jeopardize the sensors' physical safety.

Since non-rechargeable batteries are usually used to power sensor nodes in WSNs, energy efficiency is critical to the network's longevity and functionality (Yick, Mukherjee, & Ghosal, 2008).

Table 1.1: WSN and Their Memory Spaces

Sensor Node	Microcontroller	Program and data memory	External memory
IMote 2.0	Marvell PXA271	32 MB SRAM	32 MB Flash
Mica2	ATMEGA 128L	4K RAM	128k Flash
TelosB	TI MSP430	10k RAM	48k Flash
Ubimote2	TI's MSP430F2618	8k RAM	116k Flash

Frequent data transmission, idle listening, and inefficient routing can rapidly drain node energy, leading to node failures and network disconnection. Consequently, energy-aware design, especially in the context of routing protocols, is essential for sustaining long-term operation. Traditional routing algorithms often employ static strategies that do not adapt to changing network conditions such as node energy levels, link quality, or traffic load. This leads to uneven energy consumption among nodes, with some depleting their power reserves prematurely while others remain underutilized. Adaptive routing algorithms have been created to overcome this restriction by dynamically modifying data transmission routes in response to current network circumstances (Pantazis, Nikolidakis, & Vergados, 2013). These algorithms can redistribute traffic loads, avoid energy-depleted nodes, and optimize routing decisions, ultimately enhancing the overall energy efficiency of the WSN. The integration of adaptive routing techniques into WSNs offers a promising solution for extending network lifetime and improving energy utilization. Building more intelligent and self-optimizing WSNs is becoming more and more possible as research continues to investigate emerging adaptive methods, such as machine learning and artificial intelligence (Rault, Bouabdallah, & Challal, 2014).

2.0 METHODOLOGY

To characterize and establish the causes of energy inefficiency in wireless sensor networks, table 1.1 shows the typical threshold value of the power consumption, and its effect in energy inefficiency, with reference to some parameter used in checking it.

Table 1.1: Causes of Energy Inefficiency in Wireless Sensor Networks (WSNs) and Threshold Values

S/N	Causes	Description	Typical Threshold Value	Value of Power due to Energy Inefficiency
1	Idle Listening	Radio remains on and listens for traffic that may not arrive	> 5 mW (during idle state)	6 mW
2	Overhearing	Receiving packets meant for other nodes	> 2 mW per overheard packet	4 mW
3	Control Packet Overhead	Excessive exchange of routing or MAC control packets	> 10% of total network traffic	12%
4	Retransmissions due to Packet Loss	Caused by collision, interference, or poor link quality	Packet loss rate > 5%	7%
5	Inefficient Routing (Long/Redundant Paths)	Use of longer or non-optimal routes increases transmission energy	Path length > 3 hops for < 50 m radius	40 hops / meter (m)
6	Data Redundancy	Transmission of duplicate or non-aggregated data	Redundancy ratio > 20%	22%
7	High Transmission Power	Sending data with more power than required	> 100 mW for < 100 m transmission	102 mW
8	Inefficient Sleep Scheduling	Nodes not switching to low-power sleep mode during inactivity	Wake time > 30% of total cycle unnecessarily	32%
9	Environmental Interference	External noise causing communication errors	Signal-to-noise ratio (SNR) < 10 dB	8dB
10	Hardware Inefficiencies	Sensors using outdated or non-optimized energy circuits	Energy consumption > 2 J per sensing action	3J

Notes:

- Thresholds may vary depending on the WSN protocol and hardware architecture.
- These values are indicative of when energy inefficiency becomes significantly detrimental to WSN operation.
- Adaptive routing algorithms can help mitigate several of these inefficiencies by optimizing routes, managing duty cycles, and reducing control overhead.

The SIMULINK model employed for energy efficiency in wireless sensor networks is depicted in Figure 2. The model includes important components that causes the energy inefficiency like Idel Listening, Overhearing, Control Packet Overhead, Retransmissions due to Packet Loss and others. The Simulink framework enables detailed modeling of channel characteristics and system parameters, allowing for characterization energy performance in WSN.

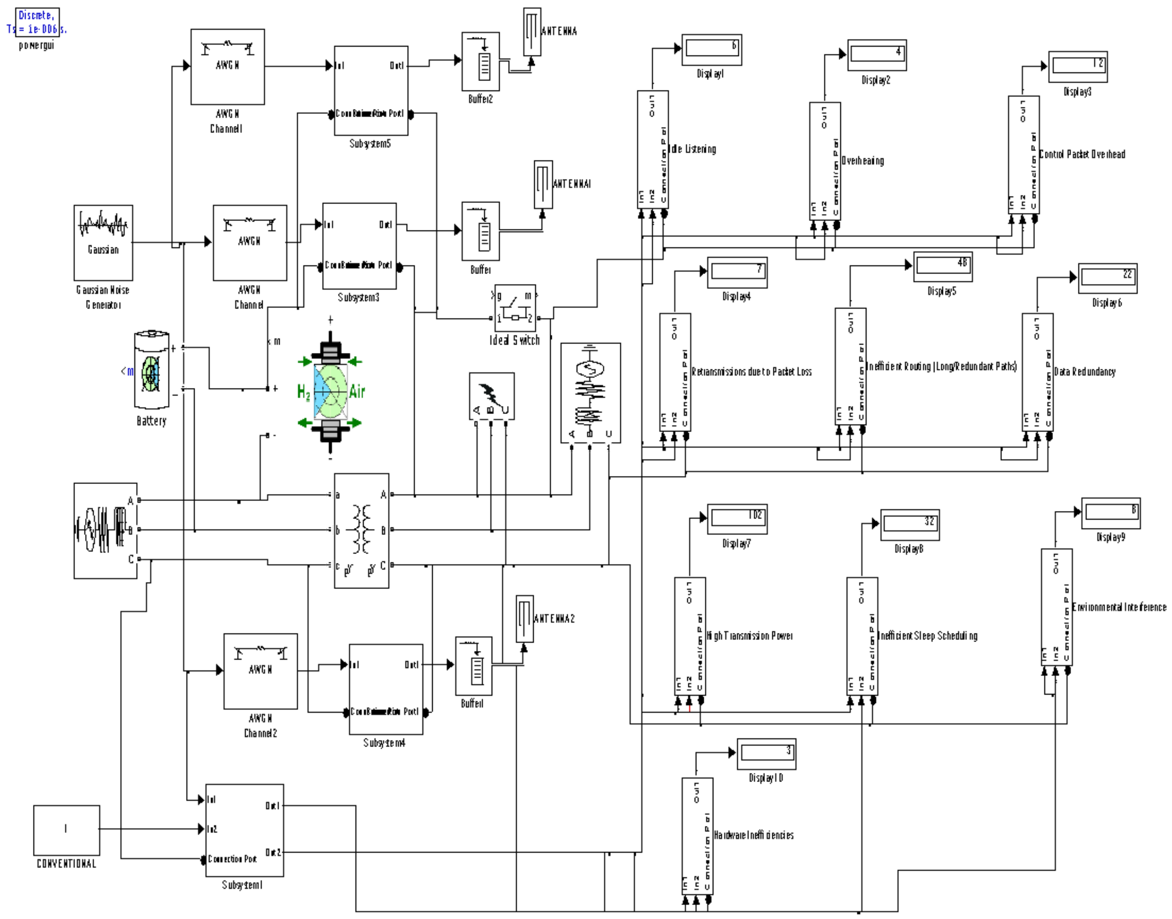

Fig. 2: Conventional Simulink Model Energy Inefficiency in WSN

2.1 Development of the Mathematical Model

To develop an optimization mathematical model for minimizing the causes of energy inefficiency in wireless sensor networks, four (4) causes of energy inefficiency from table 1.1 were selected, their MATLAB code is depicted in code 1.

Idle Listening = I

Overhearing = O

Control Packet Overhead = C

Retransmissions due to Packet Loss = R

Minimize Z = I + 2O + 3C+ 4R

Subject to

$I + 2O + 3C + 4R \leq 6$

$I + 2O + 3C + 4R \leq 4$

$I + 2O + 3C + 4R \leq 12$

$I + 2O + 3C + 4R \leq 7$

Code 1: MATLAB Code for Minimizing Energy Inefficiency in a WSN

```
% developed optimization mathematical model for minimizing the causes of
% energy inefficiency in wireless sensor networks
%Minimize Z =I + 2O + 3C+4R
%Subject to
%I+2O+3C+4R≤6
%I+2O+3C+4R≤4
%I+2O+3C+4R≤12
%I+2O+3C+4R≤7

%
%      Where
% Z is OPTIMIZED ENERGY EFFICIENCY IN WIRELESS SENSOR NETWORKS
%Idle Listening =I
%Overhearing =O
%Control Packet Overhead= C
%Retransmissions due to Packet Loss=R

    f=[-1  ;-2  ;-3;-4];
    A=[1 2 3 4; 1 2 3 4;1 2 3 4;1 2 3 4];
    b=[6;4;12;6];
    Aeq=[0 0 0 0 ];
    beq=[0];
    LB=[0 0 0 0];
    UB=[inf inf inf inf];
    [X,FVAL,EXITFLAG]=linprog(f,A,b,Aeq,beq,LB,UB)
```

Optimization terminated.

X =

3.7421
0.0282
0.0571
0.0076

FVAL =

-4.0000

EXITFLAG = 1

2.2 Development of Simulink Model for Adaptive Routing

From the conventional Simulink model for energy inefficiency in a WSN, another Simulink model was developed for the implementation of Adaptive Routing that will monitor and adjust the causes of the energy inefficiency in a WSN, this is shown in Figure 3. The algorithm that would implement the process was developed as in Code 2.

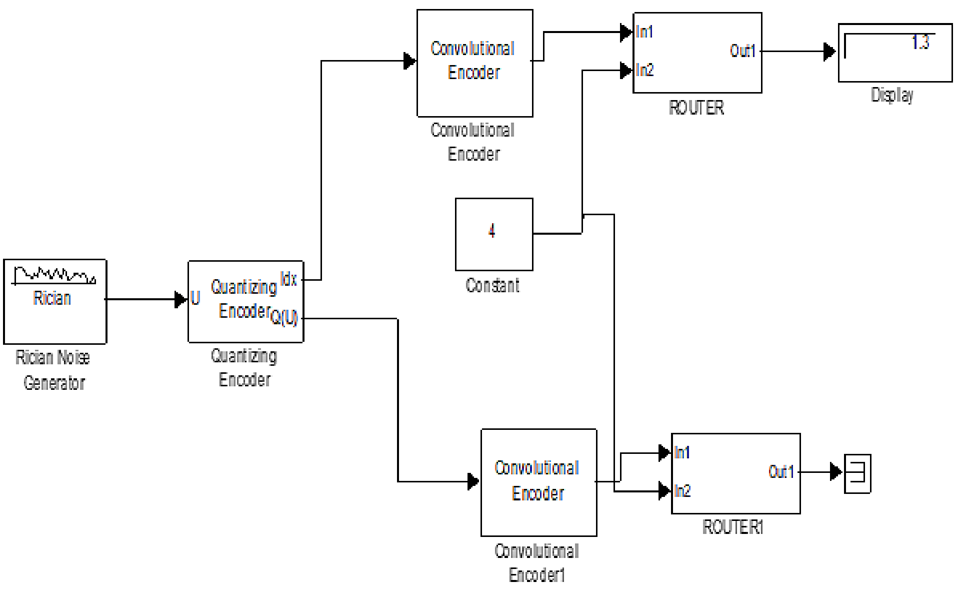

Fig.3: Simulink Model for Adaptive Routing in a WSN

Code 2: Algorithm that would Implement the Adaptive Routing

1. Characterize and establish the causes of energy inefficiency in wireless sensor networks
2. Identify Idle Listening
3. Identify Overhearing
4. Identify Control Packet Overhead
5. Identify Retransmissions due to Packet Loss
6. Identify Inefficient Routing (Long/Redundant Paths)
7. Identify Data Redundancy
8. Identify High Transmission Power
9. Identify Inefficient Sleep Scheduling
10. Identify Environmental Interference
11. Identify Hardware Inefficiencies
12. Design a SIMULINK model for energy efficiency in wireless sensor networks and integrate 2 through 11
13. Develop an optimization mathematical model for minimizing the causes of energy inefficiency in wireless sensor networks
14. Design a SIMULINK model for adaptive routing
15. Integrate 13 and 14
16. Integrate 15 into 12
17. Did the causes of energy inefficiency in wireless sensor networks minimize when 15 was integrated into 12?
18. IF NO go to 16
19. IF YES go to 20
20. Optimized energy efficiency in wireless sensor networks
21. Stop
22. End

2.4 Designing of the Simulink Model Optimization of Energy Efficiency in a WSN

To design a SIMULINK model shown in Figure 4, for optimizing energy efficiency in wireless sensor networks using adaptive routing algorithms. The conventional Simulink and the model for Adaptive Routing algorithm were taken into considerations. The appropriate communication blocks from MATLAB Simulink library for communication, with adjustment based on the mathematical model was used to develop the model for optimization of energy efficiency.

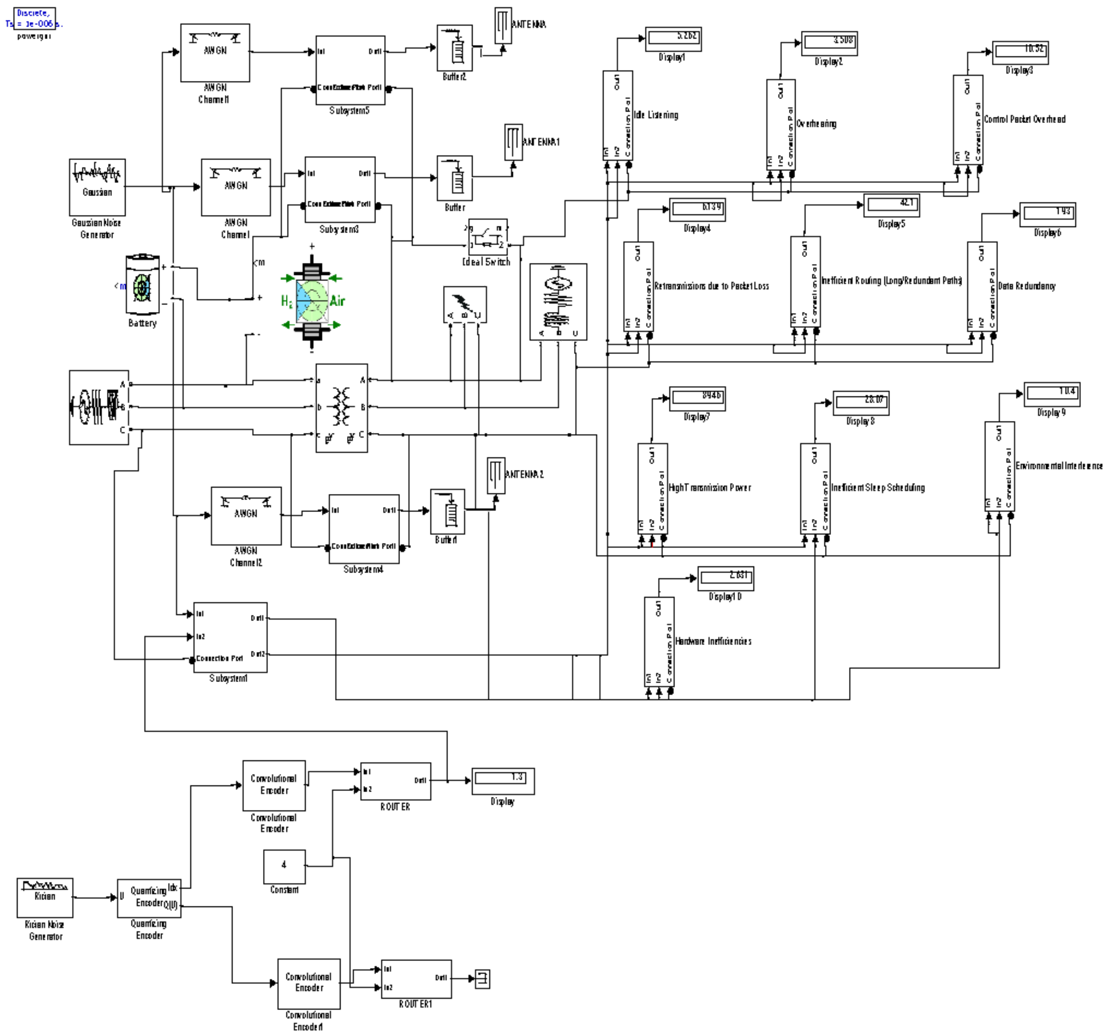

Fig.4: Simulink Model Optimization of Energy Efficiency in a WSN

To validate and justify the percentage improvement in the reduction of the causes of energy inefficiency in wireless sensor networks with and without adaptive routing algorithms, the following percentage of improvements was calculated.

i. To find percentage improvement in the reduction of Idle Listening that causes energy inefficiency in wireless sensor networks with adaptive routing algorithms

Conventional Idle Listening = 6 mW

Adaptive routing algorithms Idle Listening = 5 mW

%improvement in the reduction of Idle Listening that causes the energy inefficiency in wireless sensor networks with adaptive routing algorithms =

$$\frac{\text{Conventional Idle Listening - Adaptive routing algorithms Idle Listening}}{\text{Conventional Idle Listening}} \times \frac{100\%}{1}$$

%improvement in the reduction of Idle Listening that causes energy inefficiency in wireless sensor networks with adaptive routing algorithm =

$$\frac{6\text{ mW} - 5\text{ mW}}{6\text{ mW}} \times \frac{100\%}{1}$$

%improvement in the reduction of Idle Listening that causes energy inefficiency in wireless sensor networks with adaptive routing algorithms = **16.7%**

ii. To find percentage improvement in the inefficient routing causes that energy inefficiency in wireless sensor networks with adaptive routing algorithms

Conventional inefficient routing = 40 hops / meter

Adaptive routing algorithms inefficient routing =52 hops / meter

%improvement in the inefficient routing that causes energy inefficiency in wireless sensor networks with adaptive routing algorithms =

$$\frac{\text{Adaptive routing algorithms inefficient routing-Conventional inefficient routing}}{\text{Conventional inefficient routing}} \times \frac{100\%}{1}$$

%improvement in the inefficient routing that causes energy inefficiency in wireless sensor networks with adaptive routing algorithms =

$$\frac{52\text{ hops / meter} - 40\text{ hops / meter}}{40\text{ hops / meter}} \times \frac{100\%}{1}$$

%improvement in the inefficient routing that causes energy inefficiency in wireless sensor networks with adaptive routing algorithms = **40%**

3.0 RESULTS AND DISCUSSION

The comparison between the conventional and the adaptive routing algorithm for idle listening and inefficient routing that causes energy inefficiency in a WSN were depicted in Tables 3.1 and 3.2.

Table 3.1: Comparison of Conventional and Adaptive Routing Algorithms Idle Listening that causes Energy Inefficiency in Wireless Sensor Networks

Time (s)	**Conventional Idle Listening that causes energy inefficiency in wireless sensor networks(mW)**	**Adaptive routing algorithms Idle Listening that causes energy inefficiency in wireless sensor networks(mW)**
1	6	5
2	6	5
3	6	5
4	6	5
10	6	5

Table 3.2: Comparison of Conventional and Adaptive Routing Algorithms Inefficient Routing that Causes Energy Inefficiency in Wireless Sensor Networks

Time (s)	**Conventional inefficient routing that causes energy inefficiency in wireless sensor networks (hops / meter)**	**Adaptive routing algorithms inefficient routing that causes energy inefficiency in wireless sensor networks (hops / meter)**
1	40	52
2	40	52
3	40	52
4	40	52
10	40	52

4.0 CONCUSSION

Optimizing energy efficiency in Wireless Sensor Networks (WSNs) is essential for enhancing network longevity, reliability, and overall performance. This study has demonstrated that adaptive routing algorithms offer a viable and effective solution to the energy challenges inherent in WSNs. Unlike traditional static routing techniques, adaptive algorithms dynamically respond to changes in node energy levels, network topology, and traffic conditions, thereby distributing energy consumption more evenly across the network. This dynamic behavior not only reduces the likelihood of early node failures but also helps maintain network connectivity and data integrity over an extended period. The implementation of adaptive routing strategies significantly improves energy utilization, reduces data latency, and enhances the scalability of WSNs for various applications such as environmental monitoring, industrial automation, and security systems. Future research could explore the integration of intelligent systems such as artificial intelligence and machine learning to further refine routing decisions and enable real-time network optimization. Ultimately, adaptive routing presents a critical advancement in achieving sustainable and energy-efficient wireless sensor network deployment.

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