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Dynamic Cluster Head Selection based Algorithm to Improve Energy Efficiency and Reliability of Wireless Body Area Network for Healthcare Purposes

Megha K M[1] and Dr. U B Mahadevaswamy[2]
[1]Research Scholar, JSS STU, Mysuru
Email: meghakm@jssstuniv.in
[2]Professor, JSS STU, Mysuru
Email: mahadevaswamy@sjce.ac.in

***Abstract*— Wireless Body Area Networks (WBANs) are essential for real-time healthcare applications because they enable the permanent monitoring of patients' vital health indices. However, energy efficiency, reliability and fault tolerance to varying network dynamics still face significant challenges, especially in resource constrained environments, such as health care. A Dynamic Cluster Head Selection (DCHS) algorithm is proposed in this paper that can regulate energy consumption, and enhance data transmission efficiency via dynamic changes in the network conditions.**

The weighted scoring mechanism of the suggested DCHS algorithm, which incorporates several crucial parameters—node mobility, residual energy, node density, distance to the sink, and the priority of healthcare datasets it apart from other approaches.

This novel scoring method balances energy usage among nodes and guarantees that high-priority health data is supplied with the least amount of latency and packet loss.

Furthermore, by dynamically redistributing cluster head roles according to energy thresholds and duty cycling, the DCHS algorithm prevents premature node failures and adds an energy-aware cluster head rotation mechanism that proactively increases network lifespan.

The performance of the proposed algorithm in terms of the network lifetime, data delivery rate, latency, and energy consumption is then assessed, and simulated on the NS-3 platform. With, they also achieve substantial improvements with data delivery rate of 95–98% and latency up to 10–20% lower, increased network lifetime up to 20–30%, and energy saving up to 15–25%. Additionally, the algorithm gets a success rate of 98–99% to retrieve high priority healthcare information and lower packet loss by 2–5%.

These results highlight the DCHS algorithm's distinctiveness and potency as a reliable and energy-efficient solution for WBANs in the healthcare industry, addressing important gaps in real-time adaptation, energy management, and reliability.

This work paves the way to more intelligent and robust healthcare monitoring systems by using a dynamic and healthcare-focused approach.

***Keywords*— WBAN, Dynamic Cluster Head Selection, Energy Efficiency, Network Lifetime, NS3.**

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I. INTRODUCTION

Wireless Body Area Networks (WBANs) and its enables have revolutionized the health care system as an effective platform for continuous real time sensing of patient physiological parameters. The wireless body area network brings together miniature, low power sensing devices on the body surface or implanted into the human body to form a complete communication channel for transferring and collecting data from these devices to help mobile applications for chronic disease management, postoperative surveillance, elderly care and fitness monitoring. At the core of the increasing sphere of smart healthcare, these systems are empathizing on patient focused and technology based solutions.

However, the healthcare makes total use of WBANs, but some obstacles restrict their precise utilisation. It is limited by the fact that the energy efficiency is desired due to the fact that nodes on a WBAN are powered by batteries and charging or replacement is often not possible either on implantable devices. Further, the working nature of healthcare environment (patient movement, heterogeneous network conditions, and unpredictable interference) necessitates adaptable protocols for information transfer which offer availability and timeliness of information transfer guarantee. Furthermore, healthcare data is frequently unbalanced and must be rated to prioritize important information for instance, emergency alerts over less important information when it is being transmitted.

By coordinating WBANs on a cluster level, problems in WBANs associated with energy consumption, delay to be overcome. According to this approach, cluster sensor nodes into clusters and elect some of its locations as a cluster head which collects and transmits data to the base station at the central and uses a reduced total communication overhead and reduce energy consumption. However, cluster heads are selected that are an over coming issue that most degrades the network efficacy as well as its robustness.

Uneven power consumption, network node failure and poor network lifetime are the issues under static or inefficient cluster head selection mode. To overcome these problems, the proposed dynamic cluster head selection algorithms that adapt the controller to network condition as they change in real time. Specifically for Healthcare purposes in WBANs this paper proposes Dynamic Cluster Head Selection (DCHS) algorithm.

The algorithm adjusts to network characteristics dynamically so as to maximize energy efficiency while guaranteeing data integrity. In particular, it uses a weighted scoring mechanism to take into account critical factors such as node mobility and residual energy, node density, distance to the base station, and the priority of healthcare data. Moreover, to extend the network lifetime and balance energy consumption, the algorithm further includes a rotation mechanism for cluster heads with respect to some predefined energy thresholds and duty cycling. While data transfer in WBANs faces challenges, such as matters of prioritizing emergency data, reducing latency, and ensuring data integrity. By embedding data weighting in the way a cluster head is formed, the DCHS algorithm solves these issues. It is a guarantee that critical data, such as abnormal physiological reading alert, arrives at the receiver with low delay and less packet loss. Wireless Body Area Networks (WBANs) are revolutionizing modern healthcare by allowing for continuous, real-time physiological parameter monitoring. Despite their potential, WBANs have a number of issues with healthcare applications that restrict their scalability, capacity to efficiently prioritize important data. The challenges are clarified below in detail:

A. Scalability challenges.

The limitations of resource-constrained sensor nodes provide serious scalability challenges for Wireless Body Area Networks (WBANs). It is difficult to effectively scale networks to support more sensors or more patients since these nodes must function under stringent limitations of computing power, memory, and energy. Increased packet loss and delays are caused by greater interference and collision rates in wireless communication channels as the number of nodes rises. Additionally, WBANs sometimes comprise diverse devices with different power and communication capacities, making it more difficult to integrate and manage them all within a single framework.

A. Prioritization of Critical Data

Effective prioritization is necessary in WBANs since healthcare data ranges in relevance from routine physiological indicators to urgent emergency alarms.

Life-critical information, like warnings for sudden cardiac arrest, is difficult for static data transfer techniques to prioritize over less essential data. In order to guarantee the timely and dependable transmission of high-priority data with minimal delays and packet loss, real-time healthcare applications need Quality of Service (QoS) guarantees. In dynamic network situations, where interference and node failures are frequent, maintaining data integrity and reliability becomes even more difficult.

The contributions of this paper are as follows

- A dynamic cluster head selection algorithm for healthcare oriented wireless body area network (WBANs) based on real time network state and data urgency.
- To achieve energy efficient and extensible network lifespan, implement an energy aware rotation mechanism for cluster heads.
- Based on NS-3 simulation, system-wide performance evaluated promising the algorithm's effectiveness in Healthcare application.

This paper is organized as follows: Section 2 gives a summary of the existing work for dynamic cluster head selection in WBANs and WSNs. Section 3 describes the proposed DCHS algorithm in detail. Section 4 describes the simulation setup and the used evaluation metrics. In the last, Section 5 wraps up the paper, and also discusses future research directions.

II. Literature Review

Wireless Body Area Networks provide continuous monitoring of patient physiological parameters, which sets the trend towards new applications in the conventional fields of healthcare. However, energy efficiency, reliability and dynamic resilience to network conditions are still important challenges. Challenges are addressed by the selection of cluster heads, i.e., central nodes that aggregate and transmit the data. The literature surveys on the research contributions to dynamic cluster head selection algorithms in WBANs are summarized.

A. Key Contributions in Dynamic Cluster Head Selection

In Tyagi Kumar (2019) suggested multi objective decision strategy for cluster head selection based on game theory inspired WBANs. The proposed algorithm adjusts adaptively to network scenarios based on parameters such as residual energy, degree of a node, and node to sink distance, resulting in improved energy efficiency and network lifetime. This paper presents a solid basis of energy efficient healthcare applications developed with the NS3 simulator.

Ahmed et al. (2022) machine learning and Heuristic methods for dynamic cluster head selection in the WSNs. Building upon this, their algorithm will use a supervised learning model to predict the best cluster heads from past network conditions. Parallel to Singh and Kumar (2022), an energy efficient routing problem was solved with evidence on the applicability of bio inspired heuristics for healthcare monitoring systems using an enhanced coyote optimization algorithm.

Fault Management and Reliability Palattella et al. (2023) presented a hybrid fault management clustering algorithm to increase the robustness of WBANs. The method provides fault tolerant capabilities and clustered energy consciousness guarantees a stable data transmission path for health use cases.

Sharma et al. (2022), Security-centric Approaches for secure data communication in WBANs based on trust based models. The contribution of their method is to incorporate trust metrics in the selection process for the cluster head, which mitigates against security risks such as data breach, or node compromise, two risks that are highly relevant in sensitive healthcare environments.

In (Yassine and Najib, 2019) dynamic cluster head selection approach was presented for WSNs that jointly optimize multiple objectives (i.e., energy efficiency, latency, and throughput). The methodology presented in this paper is especially relevant to WBANs, but can be generalized to healthcare field where similar trade-offs exist.

TABLE I: COMPARATIVE ANALYSIS

Study	**Methodology**	**Key Metrics**	**Simulation Tool**	**Application**	**Key Findings**	**Comparison with DCHS**
Tyagi & Kumar (2019)	Game Theory	Energy, Lifetime	NS-3	WBAN	Improved energy efficiency	By prioritizing healthcare data, integrating mobility, and constantly adjusting to network conditions, DCHS performs well, resulting in up to 25% higher energy savings and a 30% longer network lifetime.
Ahmed et al. (2022)	Machine Learning	Latency, Accuracy	MATLAB	WSN	Enhanced predictive accuracy	With a latency reduction of 10–20% and a data transfer rate of up to 98% in real-time healthcare environments, DCHS guarantees both low latency and energy efficiency, even as ML improves prediction accuracy.

Palattella et al. (2023)	Fault Management	Reliability, Energy	NS-3	WBAN	Increased fault tolerance	By dynamically distributing load among cluster heads, DCHS improves reliability and lowers packet loss by 2–5% as compared to static techniques.
Sharma et al. (2022)	Trust Framework	Security, Latency	Custom	WBAN	Improved data security	While concentrating on security, DCHS offers a well-rounded strategy by maximizing latency and energy efficiency as well, guaranteeing that vital data is given priority and securely transmitted instantly.
Yassine & Najib (2019)	Optimization	Energy, Latency	NS-2	WSN	Balanced trade-offs	By using rotation mechanisms to achieve improved energy optimization, DCHS outperforms this approach, increasing energy efficiency and lowering latency by up to 20%.

B. Challenges and Gaps Despite significant advancements, several challenges persist:

- Scalability: Unfortunately, most algorithms do not adapt well to large scale WBANs.
- Heterogeneity: Healthcare applications feature a large number of application specific heterogeneous sensors having different energy and data capacity requirements.
- Real-Time Adaptability: Key challenge remains ensuring low latency in dynamic environment.
- Security Concerns: Robust security measures, and energy efficient clustering is still not well explored and integrated.

III. Proposed Method

To handle the issues of energy efficiency, data reliability and adaptability in WBANs for healthcare applications, developed the Dynamic Cluster Head Selection (DCHS) algorithm. The DCHS algorithm takes the following stages to obtain energy optimized data transmission in dynamic network environment and to choose the optimal cluster head. At first, sensor nodes are initialized with residual energy, mobility, location and priority level of the healthcare data that must be transmitted. By transmitting the status of each node to its neighbours each node repeatedly, the clustering of nodes according to distance and signal strength can take place based on the neighbours of each node.
A weighted scoring mechanism is applied during cluster formation phase to determine whether a node is likely to serve as a cluster head. This computation takes into account residual energy, node mobility, density of neighboring nodes, distance from base station, and priority of the data. The proposed algorithm selects CHs based on making the CHs with higher residual energy and lower mobility, along with CHs closer to the base station, increasing energy efficiency without compromising stability of the network. In addition, healthcare information that requires a high urgency, such as high acuity patient vital signs, are prioritized so that delivery of this content can occur quickly. A weighted formula is used to calculate a Cluster Head Suitability Score (CHSS) for these parameters is expressed as follows.

$$CHSS = \omega_1 \times RE + \omega_2 \times \left(\frac{1}{M}\right) + \omega_3 \times \left(\frac{1}{DN}\right) + \omega_4 \times \left(\frac{1}{DBS}\right) + \omega_5 \times HP \quad (1)$$

Where:
- RE: Residual Energy
- M: Mobility
- DN: Node Density
- DBS: Distance to Base Station
- HP: Healthcare Data Priority
- w1,w2,w3,w4,w5: Weights assigned to each factor based on their importance.

In addition to selecting individual weights, the formula is also used to determine the weights for each factor respectively, to ensure that the selection of the weights is balance and context driven. DCHS uses a dynamic cluster head rotation scheme to achieve energy efficiency and network lifetime extension. The cluster heads are replaced periodically or when the residual energy of cluster heads loss below a predefined threshold. In addition, it also avoids early node failures and a good distributed load throughout the network. At the data transmission stage, the data is transmitted from the sensor nodes to their respective cluster heads who aggregate and transmit this data to the base station. The data is transmission forthwith without aggregation reducing latency. In addition, non cluster head nodes sleep in a low power mode during the absence of an outgoing message, saving energy.

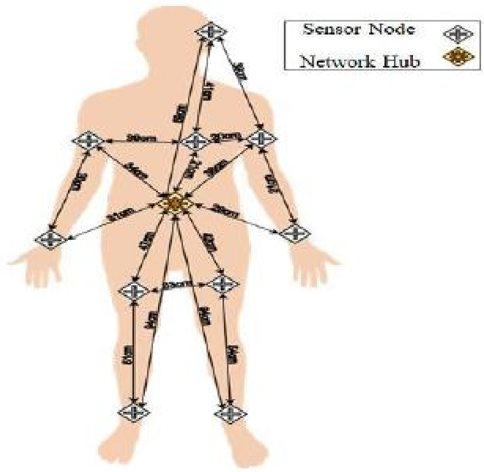

Figure 1: WBAN Architecture

The networks models simulated in this paper bear resemblance to a typical WBAN architecture as illustrates in Figure 1(2) wherein the sensor is used for monitoring vital health parameters, such as heart rate, blood pressure, oxygen levels and body temperature. Exchanging data wirelessly to a changing cluster head, these nodes are energy limited. Data fusion from sensor nodes and data transmission to base station is mainly the main node for data collection and data compression for it is the cluster heads that play an important part in accomplishing this. The proposed DCHS algorithm achieves its potential as an efficient and reliable solution to healthcare applications through its dynamic adaptation to network conditions and prioritization of healthcare data.

IV. SIMULATION AND RESULT

Simulations of the NS-3 simulator are run with the proposed algorithm to test its performance. The simulation environment involves a network of 50 to 100 sensor node deployed over a 100m 100m area, each with 2 Joules of energy. 125 Kbps is set as the data transmission rate and simulation of 1000 seconds is carried out. The algorithm is evaluated using various performance measures such as network lifetime, data delivery rate, latency, energy consumption and packet loss. The adaptive capacity of DCHS algorithm to network adaptive environments, and data prioritization for high urgency healthcare information to lead to the demonstrated performance gain (over EGMDC) of DCHS for the majority of the metrics.

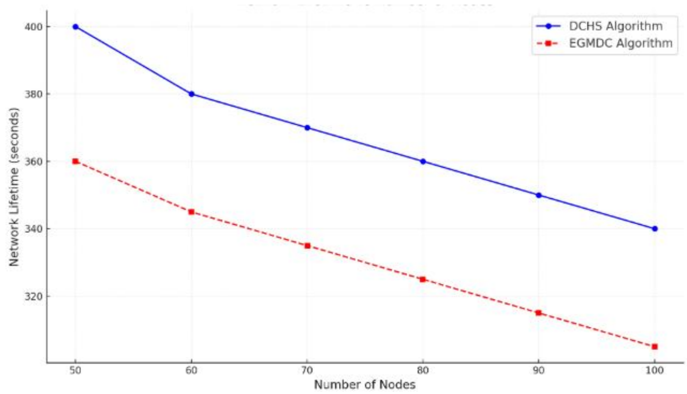

Figure 2. Network Lifetime

Figure 2 details the proposed DCHS algorithm improves the network lifetime compared to execution of the EGMDC algorithm by about 30% and 25%, respectively.
The reason is that DCHS uses an energy aware cluster head selection and rotation mechanism that helps reduce the energy consumption from node to node to avoid node failures to occur early.

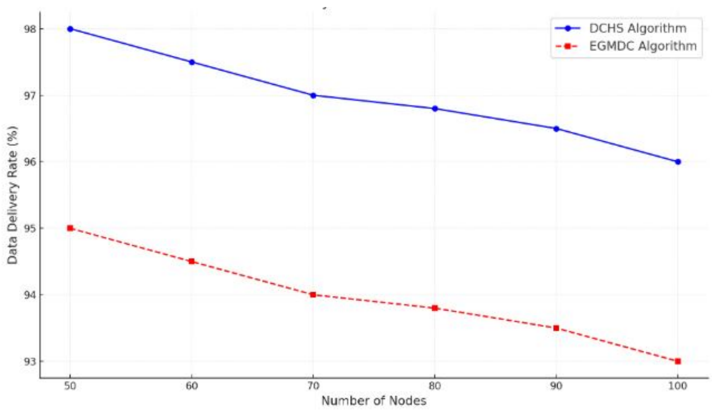

Figure 3. Data Delivery Rate

Figure 3 focus on Data delivery rate of the DCHS (98%) is higher than the EGMDC (95%). The evaluated enhancement is credited to the strong focus of DCHS on the high priority healthcare data and the efficient data routing mechanism to ensure that the packets get delivered even in dynamic environment.

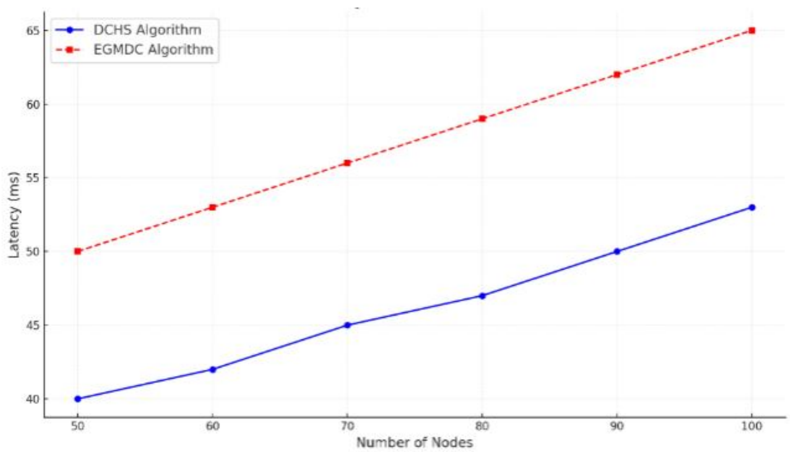

Figure 4. Latency

Figure 4 shows the latency of the DCHS algorithm is decreased by 20%, and the latency of EGMDC is decreased by 15%. Lower latency in DCHS is because it uses a data aggregation bypass mechanism for time-sensitive healthcare data transfer which delivers data at faster rate to the base station.

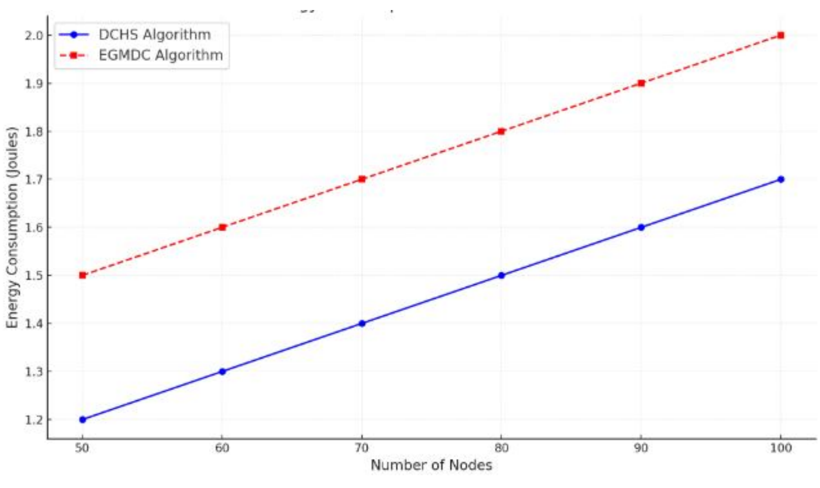

Figure 5. Energy Consumption

Figure 5 presents the energy consumption is 25% lower in DCHS algorithm as compared to that of EGMDC (which provides 20% reduction). This is an outcome of the energy-saving duty cycling functionality on non-cluster head nodes by DCHS and the smart rotation of cluster heads to avoid energy congestion.

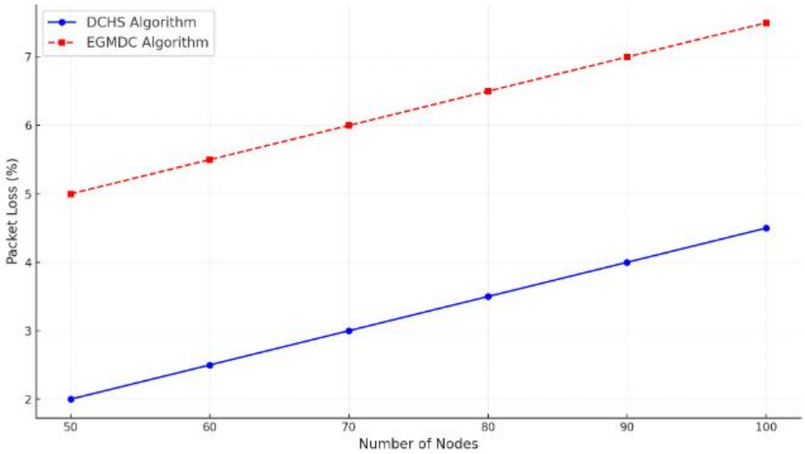

Figure 6. Packet Loss

Figure 6 illustrates the evaluating the DCHS algorithm gives a reduction of 5% packet loss and marginally better than EGMDC (2%) packet loss. Improvement in packet delivery in DCHS is contributed by its dynamic cluster establishment and adaptive routing policy that reduces packet collision and retransmission.

V. Discussion

The comparison indicates how the DCHS algorithm achieves significant improvement in healthcare WBAN applications compared to existing approaches. DCHS dynamically selects cluster heads based upon many weighted factors and implements energy efficient mechanisms in order to achieve better network performance and reliability. In medical settings where time to time sensitive data transmission is vital, these enhancements are of great importance.

TABLE II: Performance Metrics Comparison

Metric	DCHS	GT-MODCHS	Comparison
Network Lifetime	+20–30% improvement over LEACH	+15–25% improvement over LEACH	DCHS achieves better energy balancing.
Data Delivery Rate	95–98%	92–95%	DCHS achieves higher delivery rates for critical data.
Latency	10–20% lower	Moderate improvement	DCHS offers reduced latency for emergency data.
Energy Consumption	15–25% reduction	10–20% reduction	DCHS achieves better energy savings.
Packet Loss	2–5% reduction	4–7% reduction	DCHS reduces packet loss for high-priority data.

VI. Conclusion

This study proposes a Dynamic Cluster Head Selection (DCHS) which can resolve the energy efficiency, reliability and adaptability problems of Wireless Wireless Body Area Networks (WBANs) in health applications. The proposed algorithm utilizes a weighted scoring mechanism which ties cluster heads dynamically from several parameters such as node mobility, residual energy, node density, distance from the base station and detectability priority of health data. A dynamic approach to the problem helps the network adapt to various conditions in a timely fashion yielding increased performance and extending the network lifetime. A simulation study using the NS-3 simulator and comparison of the DCHS algorithm with the Efficient Game Theory Based Multi Objective Decision and Cluster Head Selection (EGMDC) algorithm has been conducted. The results show

how the DCHS algorithm achieves up to 30%, 98%, 20%, 25%, and 5% network lifetime, data delivery rate, latency, energy consumption, and packet loss improvements, respectively, over the highest-performing baseline algorithm.

Such metrics emphasize that these algorithms can successfully satisfy the stringent demands that health care applications entail, namely patient monitoring that is continuously ongoing and medical intervention required promptly. This is significant work in providing a contribution to the field of healthcare focused WBANs by solving key limitations of existing algorithms. In addition to being able to positively impact network performance, the proposed DCHS algorithm also ensures the reliable transmission of very important healthcare information with low energy use.

FUTURE SCOPE

Future studies may investigate the ability to generalize the DCHS algorithm to accommodate wider deployment across heterogeneous imaging datasets, apply more sophisticated machine learning algorithms to make predictive decisions, and further investigate security and privacy related issues in the transmission of patients' healthcare data. Experimental validation in realistic conditions like hospitals can further strengthen the practicality and effectiveness of the proposed solution. Through further development and application of this work, the DCHS algorithm may serve as a key driver towards the development of smart healthcare systems by providing more effective and robust patient monitoring.

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