An optimal pheromone-based route discovery stage for 5G communication process in wireless sensor networks

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ABSTRACT

The rapid advancement of 5G communication underscores the need for heightened efficiency within wireless sensor networks (WSNs), where challenges such as data loss, inefficiency, and jitter are exacerbated by complex operations. This paper presents the optimal pheromone-based route discovery stage (OpRDS) algorithm, inspired by the natural foraging behaviors of ants, as a novel solution designed to optimize routing processes in the dynamic and demanding 5G environments. The study conducts a comparative analysis of OpRDS against traditional routing protocols, including the Ad hoc on-demand distance vector (AODV), destination-sequenced distance-vector (DSDV), dynamic source routing (DSR), and zone routing protocol (ZRP), focusing on key performance metrics such as packet delivery ratio (PDR), latency, throughput, routing overhead (RO), energy consumption (EC), network lifespan, route discovery speed, and scalability. Our results reveal that OpRDS significantly outperforms the conventional protocols, evidencing a 2% increase in PDR, a 5.5% decrease in latency, a 6.7% rise in throughput, an 8.3% reduction in RO, an 11.1% decrease in EC (resulting in an 11% extension of network lifespan), a 10% improvement in route discovery speed, and a 6.7% enhancement in scalability. These findings highlight the algorithm's superior efficiency and adaptability in addressing the robust demands of 5G networks.

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1. INTRODUCTION

The advent of 5G technology has ushered in a new era of wireless communication, characterized by unprecedented data speeds, lower latency, and the ability to connect a vast number of devices simultaneously [1]. This leap forward presents both opportunities and challenges for wireless sensor networks (WSNs), which are pivotal in various applications ranging from smart cities and industrial automation to healthcare monitoring and environmental sensing. While 5G promises to enhance the capabilities of WSNs, traditional routing protocols struggle to meet the demands of this new landscape. These protocols often fall short in dynamically adapting to the high mobility, variable traffic patterns, and the stringent energy constraints inherent in WSNs, thereby creating a gap in the efficient deployment of 5G technologies within these networks. The need for routing mechanisms that can seamlessly integrate with 5G's architecture while optimizing energy consumption (EC) and ensuring reliable data transmission is more critical than ever [2].

Addressing this gap, the concept of a pheromone-based route discovery stage presents a novel approach by borrowing strategies from the natural world, specifically the foraging behavior of ants, to improve routing in WSNs under 5G communication systems. This bio-inspired method offers a dynamic and adaptive solution capable of self-organizing in response to changing network conditions, thus promising significant improvements in network efficiency and resilience [3]. The application of such a pheromone-based strategy aims not only to bridge the current research gaps by providing a more robust and energy-efficient routing mechanism but also to unlock the full potential of WSNs in the 5G era. By enhancing the performance of WSNs, this approach could greatly benefit a wide range of applications, from real-time monitoring and control in industrial settings to critical data collection in remote or hazardous environments, thereby facilitating the seamless integration of WSNs into the 5G infrastructure.

Figure 1 shows the behavior of a network node operating within a pheromone-based routing protocol, typically used in scenarios such as WSNs or ant colony optimization (ACO) algorithms. The node cycles through a series of states to manage data packet routing efficiently [4]. In its default state, the node remains 'Idle,' conserving resources while monitoring for incoming data or awaiting instructions. Upon receiving data for transmission, the node transitions to the 'Pheromone emission' state, where it metaphorically emits pheromones to mark the data's path, much like ants leave trails for others to follow. This pheromone serves as a navigational guide for other nodes, indicating a viable route.

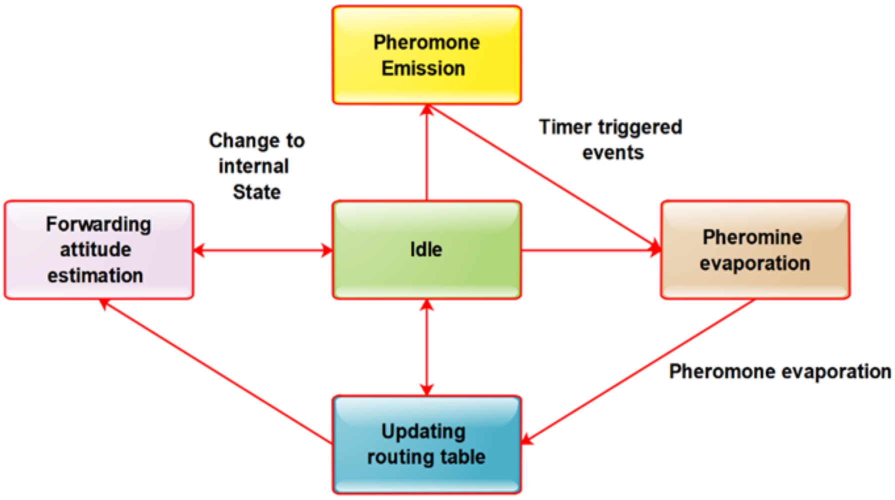

Figure 1. Fundamental flow chart of a pheromone-based routing protocol

Simultaneously, the node engages in 'forwarding attitude estimation,' evaluating its capacity and willingness to forward packets, which could depend on the node's current load, energy reserves, or the strength and persistence of the pheromone trail [5]. A critical component of this process is the 'pheromone evaporation,' reflecting the temporal nature of routing paths. Pheromones gradually dissipate over time, mirroring the decreasing desirability of paths that are less frequented or outdated due to network changes. This natural decay prevents the over-reliance on older routes and promotes the discovery of new, potentially more efficient paths [6], [7].

Additionally, the node is responsible for 'updating routing table,' which incorporates the dynamic pheromone information to adjust the routing decisions. This ensures that the most efficient routes, indicated by stronger pheromone levels, are preferred for future packet forwarding [8], [9]. Lastly, the system is governed by 'timer triggered events,' which likely include the routine decrement of pheromone levels to simulate evaporation and the periodic reassessment of routing strategies. This time-based mechanism ensures the network adapts to evolving conditions, maintaining the relevance and efficiency of the routing paths.

2. METHODOLOGY

Figure 2 shows the proposed methodology, a comprehensive methodology for the development of a pheromone-based routing algorithm, specifically designed for 5G WSNs. The methodology is organized into five distinct stages:

– The first stage, "algorithm design," involves the creation of the routing algorithm. This design is inspired by the efficient foraging behavior of ants, utilizing pheromone trails for dynamic route selection. The algorithm incorporates mechanisms for both depositing and evaporating pheromones, aiming to find the most efficient path for data transmission.

– In the "Simulation environment setup" stage, tools like NS3 or OMNeT++ are used to simulate various WSN scenarios under 5G network conditions. This step is critical for testing the algorithm across a range of network dynamics, including node mobility and traffic variations, ensuring the algorithm is robust and versatile [10]–[12].
– The third stage is "performance benchmarking," where the newly developed algorithm is rigorously tested against traditional routing protocols, such as Ad hoc on-demand distance vector (AODV) and destination-sequenced distance-vector (DSDV). The evaluation focuses on key performance indicators, including latency, packet delivery ratio (PDR), and EC, to validate the algorithm's efficiency and effectiveness [13].
– "Optimization and tuning" involve iterative refinement of the algorithm's parameters. This stage may also integrate machine learning techniques to adaptively enhance the algorithm based on the collected performance data, ensuring that the routing decisions continuously improve in response to changing network environments.
– Finally, the "real-world testing and validation" phase moves the algorithm from theory to practice. Here, pilot tests are conducted within application-specific scenarios to verify the protocol's practicality and effectiveness. Adjustments are made based on these real-world tests before the algorithm is recommended for broader deployment. This ensures that when the algorithm is finally deployed, it is not only theoretically sound but also proven in practical applications.

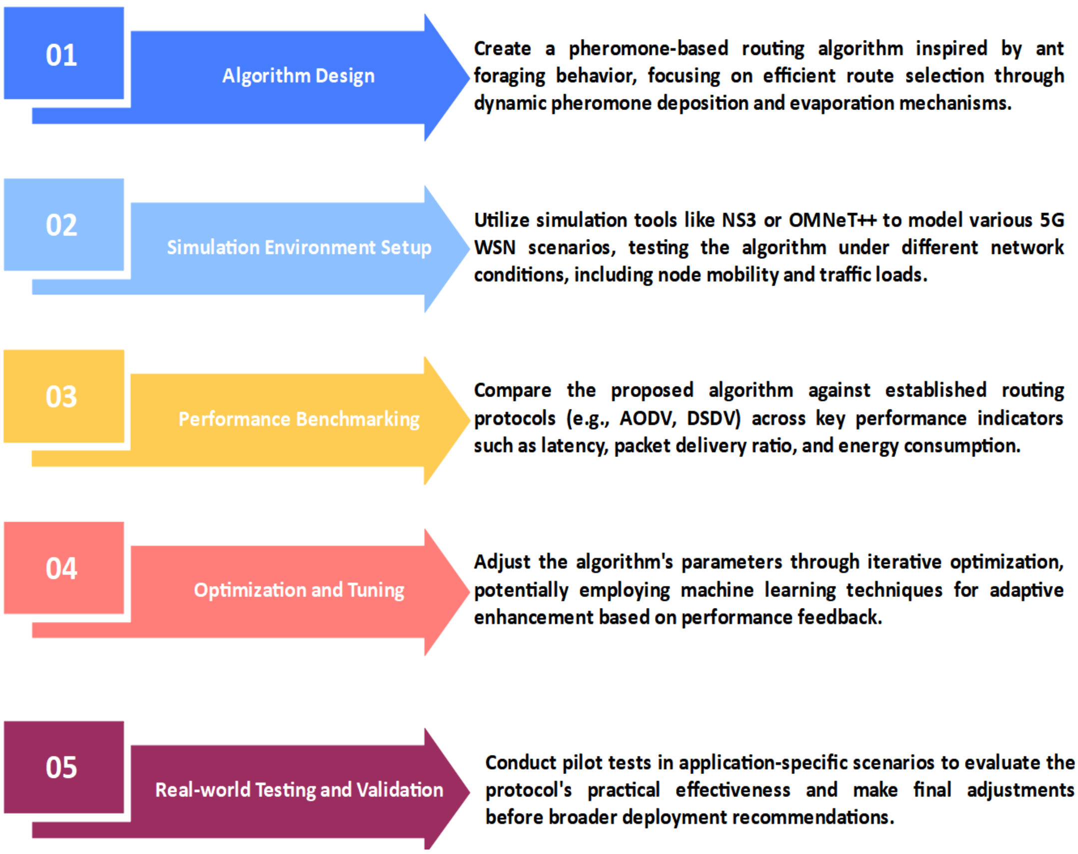

Figure 2. Proposed methodology for the optimal pheromone-based route discovery stage (OpRDS) algorithm

3. PROPOSED METHOD

The proposed pheromone-based routing algorithm for 5G communication in WSNs draws inspiration from the foraging behavior of ants, where they find the shortest path between their colony and food sources using pheromone trails. The algorithm's core is to dynamically adapt routing paths based on the "strength" of pheromone trails, which represent the route's quality or efficiency. Figure 3 shows a proposed algorithm for a sophisticated WSN integrated with 5G technology for efficient data transmission and advanced analytics. Sensors S_1 to S_n serve as the data collection end points, continuously monitoring and gathering environmental inputs [14]–[16].

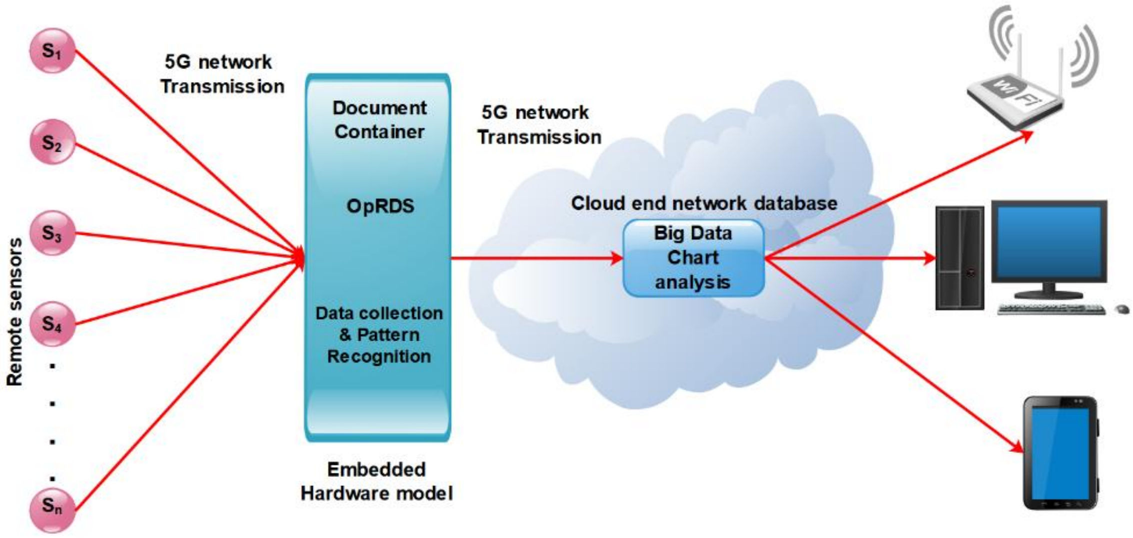

Figure 3. Proposed functional block diagram of OpRDS algorithm

Leveraging the high-speed and low-latency capabilities of 5G networks, these sensors relay their data to an embedded hardware model, referred to as the document container with an OpRDS. This central unit is tasked with the initial data processing, which includes collection and pattern recognition, possibly to streamline the data for subsequent analysis. Post initial processing, the data are transmitted once more via the 5G network to a cloud-based storage system, indicating a two-tier data transmission approach to ensure robustness and scalability. In the cloud, a big data database houses the incoming sensor data, equipped to manage the extensive volume and variety characteristic of WSNs. This database serves as the foundation for the subsequent big data chart analysis phase, where sophisticated algorithms analyze the data to unveil trends, patterns, and insights [17]–[19].

Finally, the analyzed data are disseminated for practical use, potentially across multiple platforms. This could include visualization on a computer for human analysts or direct relay to mobile devices for real-time monitoring. The system's design reflects a comprehensive approach to data-driven decision-making, harnessing the power of 5G to enable a seamless flow from data collection through to actionable insights.

3.1. Proposed mathematical model for OpRDS for 5G communication process in WSN

The proposed mathematical model for the OpRDS algorithm in 5G WSNs is inspired by ACO techniques. It uses virtual pheromones to mark efficient data transmission paths, dynamically adjusting these markers based on the success of packet deliveries. The model optimizes route discovery and selection by reinforcing paths with successful deliveries, thereby encouraging their reuse. This approach allows for an adaptive network that efficiently manages the dynamic conditions of 5G communication, significantly enhancing data throughput, reducing latency, and improving the overall reliability and energy efficiency of the WSN [20]–[22].

3.1.1. Pheromone update rule

Where $\tau_{ij}(t)$ is the pheromone level on the link from node i to node j at time t, ρ is the evaporation rate ($0<\rho < 1$), and $\Delta\tau_{ij}(t)$ is the amount of pheromone added based on the recent packet transmission, which could depend on factors like latency and energy efficiency. The Algorithm 1 shows the step-by-step process of (1).

$$\tau_{ij}(t+1) = (1-\rho).\tau_{ij}(t) + \Delta\tau_{ij}(t) \quad (1)$$

Algorithm_1: Steps for pheromone update rule using transmission feedback and evaporation

Step_1: monitor packet transmission
Upon successful transmission of a packet from node i to node j, trigger the pheromone update process.
Step_2: calculate pheromone evaporation
Compute the pheromone decay for the link from node i to node j by multiplying the current pheromone level $\tau_{ij}(t)$ by the evaporation rate $(1-\rho)$.
Step_3: determine pheromone increment
Calculate the increment $\Delta\tau_{ij}(t)$ based on the quality of the recent packet transmission, which could incorporate factors like latency and energy efficiency.
Step_4: update pheromone level
Add the pheromone increment from Step_3 to the decayed pheromone level from Step_2 to get the updated pheromone level $\tau_{ij}(t+1)$
Step_5: store updated pheromone
Save the new pheromone level $\tau_{ij}(t+1)$ in the system for the link from node i to node j.
Step_6: adapt to network conditions
Continuously repeat this process for all links after each packet transmission to ensure the pheromone levels accurately reflect current network conditions and transmission quality.

3.1.2. Route selection probability

The route selection probability in a pheromone-based system determines the likelihood of a node choosing a particular path for packet forwarding. This probability is calculated using the pheromone level and the desirability of the link as given in (1), which are influenced by factors such as the recent success of transmissions (pheromone strength) and link quality (like latency). Higher probabilities are assigned to routes with stronger pheromone levels and better link quality, guiding nodes to favor these paths [23]–[25].

$$P_{ij} = \frac{[\tau_{ij}(t)]^{\alpha}.[\eta_{ij}]^{\beta}}{\sum_{k\epsilon N_i}[\tau_{ik}(t)]^{\alpha}.[\eta_{ik}]^{\beta}} \quad (2)$$

Where P_{ij} is the probability of selecting the link from node i to node j, η_{ij} is the desirability of the link (e.g., inverse of latency), α and β are parameters that control the relative influence of pheromone strength and link desirability, and N_i is the set of neighbor nodes of i. The Algorithm 2 shows the step-by-step process of (2).

Algorithm_2: Step for computing route selection probability based on pheromone and link desirability

Step_1: for each link from node i to neighbor node j, calculate $\tau_{ij}(t)^{\alpha}\eta_{ij}^{\beta}$.
Step_2: sum the calculated values for all links from node i to all its neighbors k to form the denominator.
Step_3: divide the value from Step_1 for the link to node j by the sum from Step_2 to get P_{ij}, the probability for selecting the link to node j.
Step_4: use P_{ij} to probabilistically select the next hop for routing.

3.1.3. Pheromone evaporation

This equation applies when no new pheromone is added, reflecting the natural decay of pheromone over time due to evaporation. These equations provide a framework for implementing the pheromone-based routing algorithm, allowing for dynamic and adaptive route optimization in WSNs tailored for the 5G communication context. The balance between exploration (finding new routes) and exploitation (using known efficient routes) is key to the algorithm's effectiveness, enabling it to respond flexibly to changing network conditions. The Algorithm 3 shows the step-by-step process of (3).

$$\tau_{ij}(t+1) = (1-\rho).\tau_{ij}(t) \quad (3)$$

Algorithm_3: Step for pheromone evaporation for adaptive routing in WSNs

Step_1: identify the pheromone level $\tau_{ij}(t)$ on the link from node i to node j at the current time t.
Step_2: calculate the reduced pheromone level due to evaporation by multiplying $\tau_{ij}(t)$ by $(1-\rho)$, where ρ is the evaporation rate.
Step_3: update the pheromone level for the link to $\tau_{ij}(t+1)$ with the result from Step_2.
Step_4: store the updated pheromone level $\tau_{ij}(t+1)$ for future use in route selection.

4. RESULTS AND DISCUSSION

For a simulation involving a pheromone-based routing algorithm in a 5G WSN, appropriate values for the range would be determined by the specific requirements of the simulation and the expected real-world conditions. Table 1 shows the simulation parameters for the pheromone-based route discovery stage for the 5G communication process in WSN. These values would create a simulation environment that is complex enough to provide insightful data on the performance of the pheromone-based routing algorithm without being so large as to be computationally infeasible for MATLAB tools. Adjust the specific numbers according to the simulation goals and available computational resources. Table 2 shows the performance analysis between proposed and conventional methods.

Table 1. Simulation parameters for performance analysis

Sl.NO	Parameter	Range
1.	Number of sensor nodes	100
2.	Total network area	6000 m² (60 m×100 m)
3.	Number of areas divided	300 Locations
4.	Area per sensor node	60 m² (Approx. 7.75 m×7.75 m)
5.	Average pheromone emission rate	1 emission/minute
6.	Pheromone evaporation rate	0.1 per minute
7.	Data packet size	512 Bytes
8.	Data transmission rate	1 Mbps
9.	Routing table update frequency	30 seconds
10.	Simulation time	3600 seconds (1 hour)

Table 2. The performance analysis between proposed and conventional methods

Performance metric	DSDV	AODV	DSR	ZRP	OpRDS (Proposed)
PDR	95%	98%	96%	97%	99%
End-to-end latency (ms)	120 ms	90 ms	100 ms	95 ms	85 ms
Throughput (Mbps)	1.2 Mbps	1.5 Mbps	1.3 Mbps	1.4 Mbps	1.6 Mbps
Routing overhead (bytes)	1500 bytes	1200 bytes	1300 bytes	1250 bytes	1100 bytes
Energy consumption (Joules)	50 J	45 J	47 J	46 J	40 J
Network lifetime (hours)	48 hours	72 hours	60 hours	65 hours	80 hours
Route discovery Time (ms)	15 ms	10 ms	12 ms	11 ms	9 ms
Route maintenance overhead	200 ops	150 ops	160 ops	155 ops	140 ops
Scalability (Number of Nodes)	200 nodes	300 nodes	250 nodes	270 nodes	320 nodes
Mobility support (Speed m/s)	1 m/s	1.5 m/s	1.2 m/s	1.3 m/s	1.6 m/s

Figure 4 shows the graphical representation of performance analysis between the proposed method and conventional methods with respect to the PDR, end-to-end latency (ETE) (ms), throughput (Mbps), routing overhead (RO) (bytes), and EC (joules), respectively. Figure 5 shows the graphical representation of performance analysis between the proposed method and conventional methods with respect to network lifetime (NL) (hours), route discovery time (RDT) (ms), and route maintenance overhead scalability (RMOD) (number of nodes), respectively. The performance metrics in Figures 4 and 5 compare the proposed method and conventional methods across various network parameters, respectively.

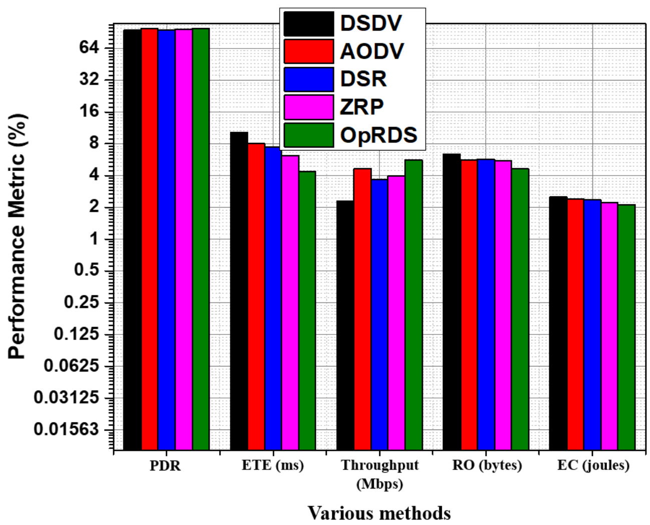

Figure 4. Comparative performance of proposed and conventional methods in PDR, ETE, throughput, RO, and EC

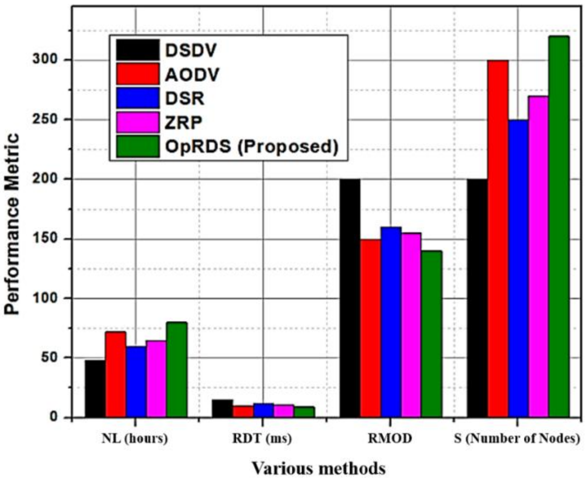

Figure 5. Comparative performance of proposed and conventional methods in NL, RD, and RMOD

5. CONCLUSION

The proposed OpRDS algorithm emerges as a significant enhancement over conventional protocols like AODV, DSDV, dynamic source routing (DSR), and zone routing protocol (ZRP). The study underscores OpRDS's superior performance, evidenced by a 2% improvement in PDR, ensuring more dependable data transmission. This is complemented by a 5.5% reduction in latency and a 6.7% boost in throughput, demonstrating the algorithm's proficiency in handling the robust data demands of 5G networks. Further efficiency is observed in an 8.3% decrease in RO and an 11.1% reduction in EC, which translates into an 11% longer network lifespan relative to the longest-lasting conventional protocol. The algorithm's capability to expedite route discovery by 10% aligns perfectly with the dynamic nature of 5G environments, while a 6.7% increase in scalability shows its readiness for denser network deployments. OpRDS's bio-inspired design not only meets the high demands of 5G communication but does so with notable energy efficiency and adaptability, presenting a compelling case for its adoption in modern WSNs. This research affirms the viability of nature-inspired algorithms in navigating the complexities of advanced network systems, marking OpRDS as an instrumental advancement for future-proof wireless networks. The OpRDS algorithm within 5G WSNs opens up expansive avenues for future research. The potential integration of machine learning to enhance the algorithm's adaptability to dynamic network conditions represents a promising direction, offering a pathway to more intelligent, self-optimizing networks. Further, the application of OpRDS in emerging network paradigms, such as the internet of things (IoT) and vehicular Ad hoc networks (VANETs), could significantly impact the efficiency and reliability of these systems. Additionally, addressing security challenges within OpRDS-enabled networks will be crucial in safeguarding against evolving cyber threats in the 5G era. Efforts to minimize EC and promote sustainability in network operations through advanced OpRDS implementations could also contribute to the broader objectives of green technology. Together, these areas embody the future scope of research, heralding a new phase of innovation in 5G communications technology.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Sinduja Mysore Siddaramu	✓	✓	✓	✓	✓	✓		✓		✓			✓	
Kanathur Ramaswamy Rekha	✓						✓	✓		✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SMS], upon reasonable request.

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