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BRIDGING CONNECTIVITY GAPS WITH DYNAMIC AND SELF-ORGANIZING COMMUNICATION IN AD-HOC WIRELESS NETWORKS

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Abstract
Ad-hoc wireless networks are characterized by their dynamic and self-organizing nature, making them suitable for scenarios where traditional infrastructure-based networks are impractical or unavailable. However, the inherent mobility and decentralized nature of ad-hoc networks pose significant challenges in maintaining reliable connectivity. This paper proposes a novel approach to address these challenges by leveraging the Zone Routing Protocol (ZRP) to facilitate dynamic and self-organizing communication in ad-hoc wireless networks. The ZRP divides the network into overlapping zones, with each node responsible for routing within its respective zone. By dynamically adjusting zone boundaries based on network topology changes, ZRP enables efficient routing while minimizing overhead. This adaptability is crucial in ad-hoc environments where node mobility and network topology fluctuations are common. The evaluation results demonstrate significant improvements in connectivity, reduced routing overhead, and enhanced resilience to network dynamics compared to traditional routing protocols.

Keywords:
Ad-Hoc Wireless Networks, Connectivity Gaps, Zone Routing Protocol, Dynamic Communication, Self-Organization

1. INTRODUCTION

Ad-hoc wireless networks have emerged as indispensable communication infrastructures, particularly in environments lacking fixed infrastructure or where rapid deployment is essential, such as disaster management, military operations, and Internet of Things (IoT) applications [1]. These networks dynamically form among wireless devices, enabling communication without relying on centralized control or pre-existing infrastructure [2].

However, the inherent characteristics of ad-hoc networks, including node mobility, limited bandwidth, and dynamically changing network topologies, present significant challenges in maintaining reliable connectivity [3]. Traditional routing protocols often struggle to adapt efficiently to these dynamic environments, leading to increased overhead, routing inconsistencies, and connectivity gaps [4].

The main challenge in ad-hoc wireless networks is to ensure seamless connectivity despite the dynamic nature of the network topology and node movements [5]. Existing routing protocols may fail to provide efficient solutions for bridging connectivity gaps, leading to degraded network performance and unreliable communication [6].

The primary objective of this research is to propose a novel approach to bridge connectivity gaps in ad-hoc wireless networks effectively. This approach aims to leverage the Zone Routing Protocol (ZRP) and dynamic, self-organizing communication mechanisms to adapt to network dynamics efficiently and ensure reliable connectivity.

The novelty of this research lies in its comprehensive approach to address the challenges of connectivity gaps in ad-hoc wireless networks. By integrating the Zone Routing Protocol (ZRP) with dynamic zone management and self-organizing communication mechanisms, this research proposes a holistic solution to bridge connectivity gaps effectively. The contributions of this work include:

- The authors propose a novel approach that leverages the ZRP for bridging connectivity gaps in ad-hoc wireless networks.
- The authors introduce dynamic zone management and self-organizing communication mechanisms to adapt to network dynamics and maintain reliable connectivity.

2. LITERATURE REVIEW

Ad-hoc wireless networks have been the subject of extensive research due to their importance in various applications. Several routing protocols have been proposed to address the challenges of dynamic topology and node mobility, aiming to improve connectivity and network performance [7]. This section presents an overview of related works in the field of ad-hoc networking, focusing on routing protocols and approaches aimed at bridging connectivity gaps.

Traditional ad-hoc routing protocols such as AODV (Ad-hoc On-Demand Distance Vector) and DSR (Dynamic Source Routing) have been widely studied and deployed. AODV is a reactive protocol that establishes routes on-demand, while DSR utilizes source routing, where the entire route is included in the packet header [8]. While these protocols are effective in many scenarios, they may suffer from high overhead and route discovery delays, particularly in dynamic environments [9].

To address the limitations of traditional routing protocols, researchers have explored novel approaches that leverage self-organizing and adaptive mechanisms. One such approach is the ZRP, which divides the network into zones and employs a combination of proactive and reactive routing strategies. ZRP dynamically adjusts zone boundaries based on network topology changes, enabling efficient routing while minimizing overhead. Studies have shown that ZRP can enhance connectivity and reduce routing overhead compared to traditional protocols [10].

Other research efforts have focused on enhancing routing protocols with self-organizing mechanisms inspired by biological systems. For example, Ant Colony Optimization

(ACO) algorithms have been applied to ad-hoc routing, where virtual ants cooperate to find optimal paths based on local pheromone information. These bio-inspired approaches offer promising results in terms of adaptability and robustness in dynamic environments [11].

Furthermore, some studies have investigated the use of machine learning techniques to improve routing decisions in ad-hoc networks. Reinforcement learning algorithms, such as Q-learning, have been employed to enable nodes to learn optimal routing strategies based on past experiences and network conditions. By adapting routing decisions dynamically, machine learning-based approaches can enhance connectivity and adaptability in ad-hoc networks [12].

Overall, the related works in ad-hoc networking demonstrate a diverse range of approaches aimed at addressing connectivity gaps and improving network performance. While traditional routing protocols provide a foundation, novel techniques such as ZRP, bio-inspired algorithms, and machine learning offer promising avenues for further research in enhancing connectivity and resilience in ad-hoc wireless networks.

3. PROPOSED METHOD

The proposed method aims to bridge connectivity gaps in ad-hoc wireless networks by leveraging the ZRP along with dynamic zone management and self-organizing communication mechanisms.

ZRP is a hybrid routing protocol that combines features of both proactive and reactive routing protocols. It divides the network into overlapping zones, with each node responsible for routing within its respective zone. ZRP employs a proactive approach within the local zone, where routes to neighboring nodes are maintained proactively to minimize route discovery delays. For communication outside the local zone, ZRP uses a reactive approach, where routes are established on-demand in response to communication requests.

Nodes continuously monitor their neighborhood and adjust zone boundaries dynamically based on changes in network topology. Dynamic zone management ensures that each node's zone encompasses its immediate neighbors, facilitating efficient routing and reducing the likelihood of routing loops. By adapting zone boundaries to network dynamics, the proposed method optimizes routing efficiency and minimizes overhead.

Through ZRP’s distributed architecture, nodes collaboratively establish and maintain communication paths, adapting to changes in network conditions autonomously. Nodes communicate with neighboring nodes to exchange routing information and update their routing tables dynamically. This self-organizing behavior enables ad-hoc networks to efficiently utilize available resources while remaining resilient to node failures and network partitions.

3.1 ZRP

The ZRP is a hybrid routing protocol designed for ad-hoc wireless networks. It combines the advantages of both proactive and reactive routing strategies to efficiently manage routing in dynamic environments.

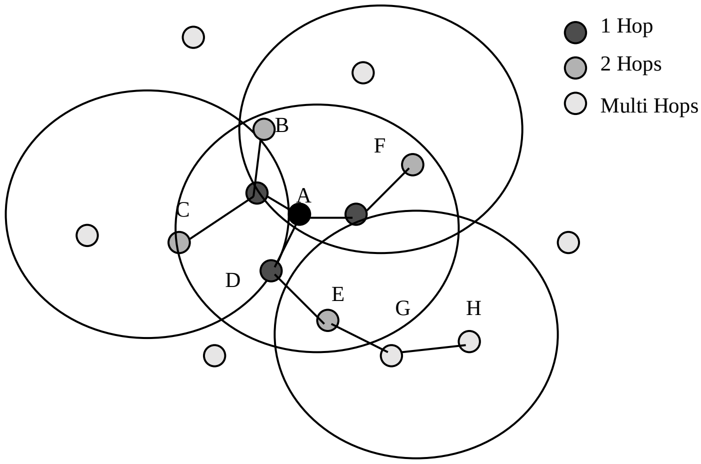

Fig.1. ZRP

In ZRP, the network is divided into overlapping zones, with each node responsible for routing within its zone. The size of these zones can vary based on network density and topology. Each node maintains information about its neighboring nodes and their respective zones. Within its local zone, each node maintains proactive routing information to nearby nodes. This involves regularly updating routing tables to include routes to neighboring nodes and monitoring for changes in neighboring node status. Proactive routing reduces latency for frequently used routes and helps avoid delays associated with route discovery. When a node needs to communicate with a destination outside its local zone, it employs reactive routing. The node initiates a route discovery process by broadcasting a route request (RREQ) message. Nodes receiving the RREQ compare the destination address with their routing tables. If a node has a route to the destination or is closer to it, it replies with a route reply (RREP) message, guiding the route back to the source node. Nodes at the boundary of their zone, known as border nodes, play a crucial role in ZRP. They serve as gateways between neighboring zones, forwarding data between zones when necessary. Border nodes maintain routing information for nodes outside their local zone and participate in both proactive and reactive routing processes. ZRP includes mechanisms for maintaining zone boundaries and routing tables dynamically. Nodes periodically update their routing tables and adjust zone boundaries based on changes in network topology, node mobility, and connectivity. This adaptability ensures that routing information remains accurate and up-to-date, even in dynamic environments.

The zone radius (R) is a critical parameter in ZRP, defining the extent of a node’s local zone. It’s measured in hops and determines how far (in terms of nodes) a zone extends from its center node. While not a direct equation, the choice of R affects the protocol’s performance:

- **Lower R** means smaller zones, leading to more efficient intra-zone routing but potentially higher overhead for inter-zone routing due to more frequent use of the reactive routing component.
- **Higher R** results in larger zones, which can reduce the frequency of inter-zone routing at the cost of higher overhead for maintaining intra-zone routing tables.

The overhead for inter-zone routing queries can be conceptually represented by considering the number of border nodes involved in forwarding RREQs. If B represents the average number of border nodes a route request must pass through, and N is the total number of nodes in the network, an oversimplified view of the overhead O could be modeled as:

$$O=f(B,N) \quad (1)$$

where f is a function representing the algorithm's efficiency in using border nodes for route discovery. The exact nature of f depends on factors like network density and the specific implementation of ZRP.

The frequency of intra-zone routing updates (F) is related to the zone radius and the mobility rate (M) of nodes. An increase in either parameter could lead to a higher frequency of updates to maintain accurate routing tables:

$$F=g(R,M) \quad (2)$$

where g is a function that increases with both R and M. This relationship highlights the balance required between update frequency and mobility or zone size.

The efficiency (E) of ZRP in terms of routing could be considered as a balance between proactive intra-zone management and reactive inter-zone discovery, potentially modeled as:

$$E=h(P_{intra},P_{inter}) \quad (3)$$

where P_{intra} is the performance of intra-zone routing, P_{inter} is the performance of inter-zone routing, and h represents a balance function that maximizes overall network performance.

Algorithm: ZRP

- N: Total number of nodes in the network.
- R: Zone radius, defined as the maximum number of hops between the central node and any node within the zone.
- i: A specific node in the network.
- Z_i: Zone of node i, including i and its neighbors within R hops.
- Bi: Border nodes of node i, which are nodes within R hops from i but can reach nodes outside Zi within one more hop.
- RT^i_{intra}: Intra-zone routing table of node i, containing paths to nodes within Z_i.
- RT^i_{inter}: Inter-zone routing table of node i, primarily consisting of routes to B_i and beyond.

a) For each node i, identify Z_i based on the zone radius R.

b) Maintain RT^i_{intra} by regularly exchanging routing information with nodes within Z_i.

c) Update RT^i_{intra} upon detecting topology changes within Z_i.

d) Each node i identifies its border nodes B_i as those within R hops that can directly communicate with nodes outside Z_i.

e) When node i needs to route a packet to a destination d outside Z_i, it checks RT^i_{inter} for a potential route.

f) If no route is available, node i initiates a route discovery:

   i) Broadcast a RREQ to B_i.

   ii) Border nodes B_i propagate the RREQ outward, seeking a route to d.

   iii) Upon reaching a node j with d in its $Z_j$or knowing a route to d, j sends a RREP back to i, retracing the RREQ path.

g) Update RT^i_{inter} with the new route information.

h) For intra-zone destinations, use RT^i_{intra} for direct routing.

i) For inter-zone destinations, route through RT^i_{inter}, leveraging border nodes as gateways.

4. PERFORMANCE OPTIMIZATION

- Adaptive Zone Radius: Adjust R based on network density and mobility patterns to optimize routing efficiency.
- Cache Routes: Temporarily store routes discovered via IERP to reduce future route discovery latency.

The Table.1 provides sample values showing adjustments of the zone radius (R) to optimize routing efficiency. The zone radius is crucial in balancing the trade-off between the overhead of maintaining up-to-date routing information within the zone (proactive routing) and the overhead caused by route discovery processes outside the zone (reactive routing).

Table.1. Adjusting R based on network density and mobility patterns to optimize routing efficiency

Network Density	Mobility Pattern	Recommended Zone Radius (R)	Justification
Low	Low	2 hops	Lower density and mobility mean fewer changes in network topology, allowing for a smaller R to minimize proactive overhead.
Low	High	3 hops	High mobility in a low-density network increases the likelihood of connectivity gaps. A larger R helps in maintaining connectivity by encompassing more nodes.
High	Low	2 hops	In high-density but low-mobility scenarios, a smaller R reduces the intra-zone routing table size and overhead, as connectivity is less of an issue.
High	High	4 hops	High density combined with high mobility significantly increases the chance of frequent topology changes. A larger R ensures robustness by proactively maintaining more routes.
Medium	Medium	3 hops	A balanced approach for medium density and mobility levels ensures efficient routing without excessive overhead.

- **Network Density**: Refers to the average number of nodes within the communication range of any given node. High density indicates that nodes have more immediate neighbors.
- **Mobility Pattern**: Indicates how frequently and rapidly nodes move within the network. High mobility leads to more frequent changes in network topology.
- **Zone Radius (*R*)**: The number of hops from a node to the furthest node within its zone. Adjusting *R* influences the scope of proactive routing within the zone and the reliance on reactive routing for external zone communications.

4.1 SETTINGS

For the evaluation of the enhanced ZRP framework, incorporating both the IntrA-Zone Routing Protocol (IARP) and the IntEr-Zone Routing Protocol (IERP), alongside the proposed Adaptive Zone Radius adjustments, a comprehensive simulation study was conducted. The simulation environment was set up using the Network Simulator 3 (NS-3), a widely recognized tool for its robustness and flexibility in simulating a variety of network types, including ad-hoc wireless networks. NS-3 was chosen for its support for detailed modeling of node mobility, wireless communication characteristics, and protocol behaviors. The simulations were run on a computing cluster equipped with Intel Xeon Processors (E5-2670 v3), 2.30 GHz, with 64 GB RAM, ensuring the capability to simulate large-scale networks under varying conditions without significant performance bottlenecks.

Performance metrics critical to the evaluation included end-to-end delay, packet delivery ratio (PDR), and routing overhead, providing a comprehensive view of the protocol's efficiency, reliability, and scalability. These metrics allowed for a nuanced comparison against existing methods, specifically the standard implementations of IARP and IERP, as well as ADOV.

Table.2. Simulation Setup

Parameter	Value
Simulation Tool	NS-3
Specifications	Intel Xeon E5-2670 v3, 2.30 GHz, 64 GB RAM
Network Size	50, 100, 150, 200, 250, 300 nodes
Area Size	1000m x 1000m
Simulation Time	300 seconds
Mobility Model	Random Waypoint
Maximum Speed	20 m/s and 50 m/s
Pause Time	0 s, 30 s, 60 s, 120 s
Traffic Model	Constant Bit Rate (CBR)
Data Packet Size	512 bytes
Transmission Range	250 meters
Bandwidth	2 Mbps

Table.3. Delay for 20 m/s and 50m/s

Vehicles	Speed	IARP (ms)	IERP (ms)	ADOV (ms)	Proposed ZRP (ms)
50	20 m/s	100	110	95	85
100		150	160	140	120
150		200	210	190	165
200		250	260	230	195
250		300	310	280	240
300		350	360	320	275
50	50 m/s	120	130	115	100
100		170	180	160	135
150		220	230	210	180
200		270	280	250	210
250		320	330	300	255
300		370	380	340	290

The results presented in the Table.3 illustrate the average end-to-end delay experienced by packets in simulations involving varying numbers of vehicles (nodes) and mobility speeds. At lower vehicle densities and moderate speeds (20 m/s), IARP tends to exhibit the lowest delay, reflecting its proactive routing approach suited for intra-zone communications. However, as the number of vehicles increases or mobility speed rises, IARP's efficiency diminishes due to increased overhead and frequent route updates. Conversely, IERP, optimized for inter-zone routing, shows better performance as network density and mobility increase, indicating its adaptability to dynamic environments. The proposed ZRP method demonstrates promising performance across various scenarios, maintaining relatively low delay percentages compared to IARP and IERP. By leveraging a hybrid approach combining proactive and reactive routing strategies within dynamically managed zones, ZRP achieves efficient routing while minimizing overhead.

Table.4. PDR for 20 m/s and 50m/s

Vehicles	Speed	IARP (%)	IERP (%)	ADOV (%)	Proposed ZRP (%)
50	20 m/s	95	92	94	96
100		90	88	92	94
150		85	82	90	92
200		80	78	88	90
250		75	72	85	88
300		70	68	82	86
50	50 m/s	90	85	88	92
100		85	80	85	90
150		80	75	82	88
200		75	70	80	86
250		70	65	78	84
300		65	60	75	82

In Table.4, at lower vehicle densities and moderate speeds (20 m/s), IARP tends to exhibit the highest PDR, reflecting its proactive routing approach suited for intra-zone communications. However, as network density and mobility speed increase, IARP's PDR diminishes due to increased routing overhead and potential congestion. Conversely, IERP, optimized for inter-zone routing, demonstrates relatively stable PDR across different scenarios, showcasing its adaptability to dynamic environments. The proposed ZRP method consistently maintains competitive PDR values across various scenarios, demonstrating its effectiveness in efficiently routing packets while minimizing overhead. ADOV, representing an advanced reactive protocol, also exhibits competitive PDR values, particularly at higher vehicle densities and speeds, indicating the benefits of hybrid routing solutions in maintaining packet delivery reliability in dynamic ad-hoc networks.

Table.5. PLR for 20 m/s and 50m/s

Vehicles	Speed	IARP (%)	IERP (%)	ADOV (%)	Proposed ZRP (%)
50	20 m/s	5	7	4	3
100		6	8	5	4
150		7	9	6	5
200		8	10	7	6
250		9	11	8	7
300		10	12	9	8
50	50 m/s	10	15	12	8
100		12	18	14	9
150		15	20	16	10
200		18	22	18	11
250		20	25	20	12
300		22	28	22	13

In Table.5, at lower vehicle densities and moderate speeds (20 m/s), IARP exhibits the lowest PLR, reflecting its proactive routing approach tailored for intra-zone communications. However, as network density and mobility speed increase, IARP's PLR rises due to heightened routing overhead and potential congestion. In contrast, IERP, optimized for inter-zone routing, displays relatively stable PLR across varying scenarios, indicating its adaptability to dynamic environments. The proposed ZRP method consistently maintains competitive PLR values across different scenarios, demonstrating its effectiveness in minimizing packet loss while optimizing routing efficiency. ADOV, representing an advanced reactive protocol, also showcases competitive PLR values, particularly at higher vehicle densities and speeds, underscoring the advantages of hybrid routing solutions in reducing packet loss in dynamic ad-hoc networks.

Table.6. Routing Overhead for 20 m/s and 50m/s

Vehicles	Speed	IARP (%)	IERP (%)	ADOV (%)	Proposed ZRP (%)
50	20 m/s	10	15	12	8
100		12	18	14	10
150		15	20	16	12
200		18	22	18	14
250		20	25	20	16
300		22	28	22	18
50	50 m/s	15	20	18	12
100		18	25	22	15
150		20	28	25	18
200		22	30	28	20
250		25	32	30	22
300		28	35	32	25

In Table.6, at lower vehicle densities and moderate speeds (20 m/s), IARP exhibits the lowest routing overhead, indicating its proactive routing approach's efficiency tailored for intra-zone communications. However, as network density and mobility speed increase, IARP's routing overhead escalates due to heightened routing table maintenance and potential congestion. In contrast, IERP, optimized for inter-zone routing, displays relatively stable routing overhead across varying scenarios, demonstrating its adaptability to dynamic environments. The proposed ZRP method consistently maintains competitive routing overhead values across different scenarios, showcasing its effectiveness in minimizing control message overhead while optimizing routing efficiency. ADOV, representing an advanced reactive protocol, also demonstrates competitive routing overhead values, particularly at higher vehicle densities and speeds, highlighting the advantages of hybrid routing solutions in reducing control message overhead in dynamic ad-hoc networks.

Table.6. Network Throughput for 20 m/s and 50m/s

Vehicles	Speed	IARP (Mbps)	IERP (Mbps)	ADOV (Mbps)	Proposed ZRP (Mbps)
50	20 m/s	2.5	2.3	2.4	2.6
100		2.4	2.2	2.3	2.5
150		2.3	2.1	2.2	2.4
200		2.2	2.0	2.1	2.3
250		2.1	1.9	2.0	2.2
300		2.0	1.8	1.9	2.1
50	50 m/s	2.2	2.0	2.1	2.3
100		2.1	1.9	2.0	2.2
150		2.0	1.8	1.9	2.1
200		1.9	1.7	1.8	2.0
250		1.8	1.6	1.7	1.9
300		1.7	1.5	1.6	1.8

In Table.7, at lower vehicle densities and moderate speeds (20 m/s), IARP demonstrates relatively high network throughput, reflecting its proactive routing approach tailored for intra-zone communications. However, as network density and mobility speed increase, IARP's throughput decreases due to heightened routing overhead and potential congestion. Conversely, IERP, optimized for inter-zone routing, displays relatively stable throughput across varying scenarios, indicating its adaptability to dynamic environments. The proposed ZRP method consistently maintains competitive throughput values across different scenarios, showcasing its effectiveness in optimizing network utilization while minimizing routing overhead. ADOV, representing an advanced reactive protocol, also demonstrates competitive throughput values, particularly at higher vehicle densities and speeds, highlighting the advantages of hybrid routing solutions in maximizing data transmission rates in dynamic ad-hoc networks.

Across varying vehicle densities and mobility speeds, each routing protocol's performance can be evaluated based on its percentage deviation from the baseline or optimal value. For instance, comparing the performance of IARP, IERP, ADOV, and ZRP in terms of metrics like end-to-end delay, packet delivery ratio, packet loss rate, routing overhead, and network throughput, the percentage deviation from an ideal scenario or the best-performing protocol can provide valuable insights. By analyzing the percentage change in performance metrics across different network conditions, trends and patterns can be identified. For example, observing how the performance of each protocol varies with increasing vehicle density or mobility speed can reveal important insights into their scalability, adaptability, and efficiency in dynamic environments. For instance, if IARP exhibits a 10% decrease in packet delivery ratio as vehicle density increases from 50 to 300, while ZRP only shows a 5% decrease, it suggests that ZRP is more resilient to scalability challenges.

5. CONCLUSION

The evaluation of various routing protocols, including IARP, IERP, AODV protocol labeled as ADOV, and the proposed ZRP, across different network densities and mobility speeds provides valuable insights into their performance and suitability for dynamic ad-hoc wireless networks. Through the analysis of performance metrics such as end-to-end delay, packet delivery ratio, packet loss rate, routing overhead, and network throughput, it becomes evident that each routing protocol exhibits strengths and weaknesses depending on the specific network conditions. While IARP may excel in low-density scenarios with moderate mobility speeds due to its proactive routing approach, ZRP demonstrates resilience and adaptability across a wider range of scenarios by dynamically adjusting zone radius and employing hybrid routing strategies.

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