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Smart Antenna Based IEEE 802.11 MAC Protocol for Radar Networks

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ABSTRACT

This study proposes the design of an IEEE 802.11-based MAC protocol for ad hoc networks by integrating smart antenna technology, aimed at enhancing communication performance in radar tracking applications. The research uses a quantitative approach with a deductive methodology, employing simulation modeling coded in C language via Microsoft Visual C++ 2010 Express. Two types of antennas were compared: an omnidirectional antenna and a directional smart antenna. Simulations were conducted using two network topologies—string and mesh—under scenarios with and without smart antenna support. Performance was measured based on throughput, collision probability, and success rate. Results show that the smart antenna-based MAC protocol significantly outperforms the conventional setup. In the string topology, the system achieved a maximum throughput of 1.5 Mbps, a collision probability as low as 0.001 or even zero, and a perfect success rate of 1 in both topologies. These findings confirm that the integration of smart antennas into MAC protocols improves data exchange efficiency and network reliability, especially in ad hoc radar tracking environments.

1. Introduction

Wireless communication has become integral to modern information systems, driving demand for robust and adaptable networking solutions. Among these, IEEE 802.11-based ad hoc networks offer rapid deployment and infrastructure-independent connectivity, making them well-suited for mission-critical applications such as radar target tracking. In radar tracking scenarios, precise, low-latency data exchange is essential for accurately determining target coordinates and trajectories. However, conventional omnidirectional MAC protocols often struggle to meet these stringent requirements, especially under dynamic network conditions characterized by frequent topology changes, interference, and mobility constraints.

Previous studies have explored both MAC-level enhancements and smart antenna integration to address these performance limitations. For instance, Bellofiore et al. (2002) investigated the use of smart antennas in mobile ad hoc networks (MANETs) to enhance link quality, while Sanjeev (2006) provided comparative analyses of MAC protocols under varying traffic loads. Similarly, El Zooghby (2000) demonstrated the effectiveness of directional antenna systems in reducing interference and improving throughput. Despite these valuable insights, existing research typically treats antenna technology and MAC protocol designs as separate components, resulting in fragmented solutions that fail to capitalize on their combined potential. Thus, there remains a significant research gap regarding the holistic integration and evaluation of smart antenna technology directly into MAC protocol frameworks specifically tailored for radar tracking ad hoc networks.

To bridge this gap, this study presents a novel contribution by proposing a unified design and comprehensive performance analysis of an IEEE 802.11 MAC protocol explicitly integrated with smart antenna technology. The primary contribution of this research lies in its holistic approach, simultaneously addressing antenna steering strategies and MAC scheduling mechanisms within a single cohesive protocol design. By simulating and comparing performance metrics—including throughput, collision probability, and transmission success rate—in both string and mesh network topologies under scenarios with omnidirectional and directional antennas, this study quantifies the practical improvements achieved by embedding smart antennas at the MAC layer.

The outcomes of this research demonstrate significant enhancements, achieving throughput improvements of up to 1.5 Mbps, near-zero collision probability, and perfect transmission success rates. Such performance gains highlight the potential of smart antenna integration not only to address existing limitations but also to set new standards for efficiency and reliability in radar tracking communication systems. Thus, this research not only advances the theoretical understanding of integrated MAC and antenna systems but also provides a foundational framework for future practical implementations in critical radar networking environments.

2. Method

The research follows a quantitative approach with a simulation-based modeling design. The main objective is to evaluate the performance of a custom-designed IEEE 802.11 MAC protocol for ad hoc networks using smart antenna technology in radar tracking applications. The system was modeled and simulated using C language in Microsoft Visual C++ 2010 Express.

2.1 System Simulation and Modeling

The simulation system was developed using structured C programming, consisting of external dependencies, header files, source files, and resource files. The simulation generates output data in text format (*.txt or *.dat), representing network performance metrics such as throughput, collision probability, and success rate.

Two wireless network topologies—string and mesh—were modeled under two configurations: (1) using a conventional omnidirectional antenna and (2) using a smart directional antenna. Each topology was evaluated to observe the effects of smart antenna integration at the MAC protocol level.

2.2 Testing and Evaluation Method

Performance testing was carried out by comparing the simulation results of the standard IEEE 802.11 MAC protocol against the proposed MAC protocol integrated with smart antennas. The comparative analysis focused on three key performance metrics: maximum throughput, collision probability, and data transmission success rate. Data analysis was conducted using Microsoft Excel and MATLAB R2010b (version 7.11), where the collected simulation results were processed into performance graphs and tables. This comparative analysis was used to derive conclusions on the effectiveness and efficiency of the proposed MAC protocol design.

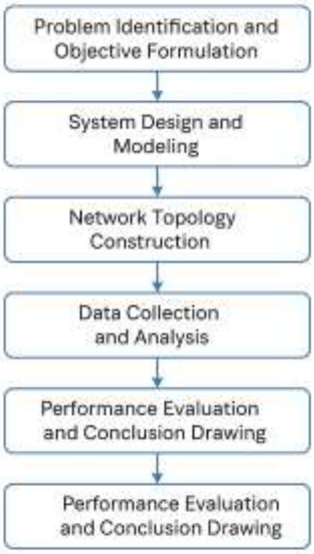

Figure 1. Research Flow and Algorithmic Framework

The research process is structured into a sequential simulation-based design and testing framework as follows:

1. Problem Identification and Objective Formulation

The study begins with identifying the performance limitations of the conventional IEEE 802.11 MAC protocol in ad hoc networks, particularly for radar tracking applications. The main objective is to enhance protocol efficiency using smart antenna integration.

2. System Design and Modeling

The MAC protocol design is carried out using the C programming language, with modular implementation that includes antenna configuration, node behavior modeling, and transmission scheduling. The system supports two antenna modes: omnidirectional (baseline) and directional smart antennas (proposed).

3. Network Topology Construction

Two network topologies are modeled: (1) String topology, representing linear node arrangements, (2) Mesh topology, representing interconnected nodes. Each topology is tested under both antenna configurations.

4. Simulation Implementation

The full system simulation is executed in Microsoft Visual C++ 2010 Express. The output includes performance logs in .txt or .dat format, capturing key metrics: throughput, collision probability, and success rate.

5. Data Collection and Analysis

Simulation outputs are processed using Microsoft Excel and MATLAB R2010b to visualize and analyze comparative performance between the baseline and proposed systems.

6. Performance Evaluation and Conclusion Drawing

Quantitative comparisons are made across scenarios to evaluate the impact of smart antennas on MAC protocol efficiency. Performance trends are analyzed, and conclusions are drawn regarding the suitability of the proposed protocol for radar tracking networks.

2.3 Data Sources

The data used in this research were entirely generated through custom-built simulation models coded in the C programming language and executed via Microsoft Visual C++ 2010 Express. The simulation was designed to emulate IEEE 802.11 MAC protocol behavior under both conventional omnidirectional and smart directional antenna configurations in two network topologies: string and mesh.

The primary data source comprises the output logs produced by the simulation system in .txt and .dat formats. These logs contain timestamped records of packet transmissions, collisions, successful receptions, and throughput values across all network nodes. Each simulation scenario was executed for 30 seconds of virtual time, during which thousands of transmission events were generated to ensure statistical significance.

The input parameters for the simulation—such as node distance, beamwidth, transmission range, carrier sensing range, contention window values (CWmin, CWmax), and retry limits—were defined based on standards from IEEE 802.11a as well as empirical values adopted from prior studies (e.g., Mamshaei, 2004; Palantei, 2009; Ma Jing, 2012). These parameter values were manually configured and verified before each simulation run.

To validate consistency, each scenario (e.g., D-MAC in mesh topology) was run multiple times under identical settings, and the resulting data were averaged to reduce the impact of outliers or random initialization artifacts. These synthetic yet reproducible data sets were then used as the basis for the quantitative performance evaluation in this study. All data processing, including aggregation, statistical summarization, and graphical visualization, was conducted using Microsoft Excel and MATLAB R2010b.

3. Result and Discussions

In this study, four network models were simulated based on the IEEE 802.11 MAC protocol standard for ad hoc radar tracking applications. The modeling was categorized based on two network topologies (string and mesh) and two antenna types (omnidirectional and directional smart antennas). All simulations were conducted using the C programming language in Microsoft Visual C++ 2010 Express.

String Topology Scenario

The first simulation scenario implements a linear string topology, where 20 nodes are arranged sequentially from Node 0 to Node 19 in a multi-hop, one-way flow. Each node is spaced 45 meters apart. The transmission range is set at 60 meters, while the carrier sensing range is 115 meters—approximately twice the transmission range—to comply with CSMA/CA mechanisms (Mamshaei, 2004). In this configuration, both omnidirectional and directional antenna modes were tested. The directional smart antenna significantly improved performance by focusing signal transmission toward the intended receiver, reducing interference and enhancing link efficiency. As reported by Miyaji (2010), the total of 19 hops in the path introduces a need for optimized scheduling, which is better achieved with directional transmission.

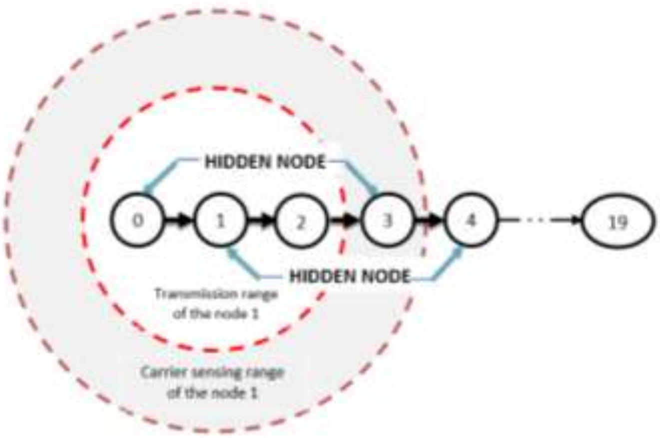

Figure 2. String Topology Scenario

Mesh Topology Scenario

The second scenario simulates a mesh topology, where 20 nodes are randomly distributed across the ad hoc network area. In this setting, each node dynamically selects its communication partner for frame exchange. The simulation includes both omnidirectional and smart antenna modes. In the directional scenario, smart antennas utilize beamforming to selectively transmit data to a specific node. For example, if Node 6 transmits to Node 10, other nodes in the network remain free to transmit simultaneously, reducing contention and increasing spatial reuse (Yazdanpanaha, 2011). This behavior mimics real-world radar tracking systems that require fast, interference-minimized communication.

System Modeling Parameters

The simulation parameters are grouped into two categories:

1. Omnidirectional Antenna System – with a constant 360° radiation pattern (Ma Jing, 2012).
2. Directional Smart Antenna System – using adaptive array antennas capable of switching between omnidirectional (0–360°) and directional (0–90°) modes depending on network demands (Palantei, 2009).

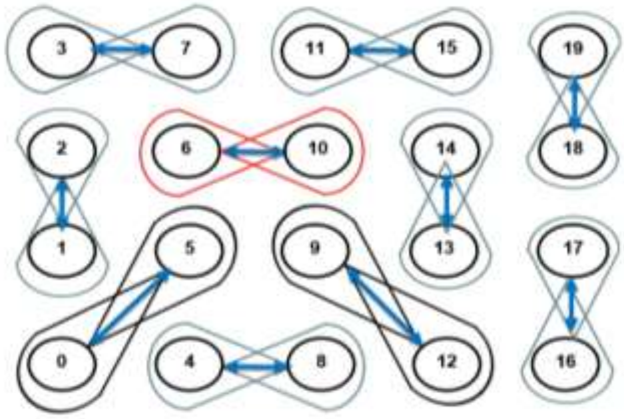

Figure 3. Mesh Topology Scenario

The overall simulation duration was set to 30 seconds for all test cases. Key MAC parameters included CWmin = 15, CWmax = 1025, and retransmission attempts capped at 7. Any failed transmission beyond this limit was considered a packet drop.

Table 1. System Parameters for Omnidirectional Antenna Configuration

Antenna Type	Omnidirectional
Beamwidth Angle	2π
Node Density	0.022 nodes/m
Total Number of Nodes	20 Nodes

Table 2. System Parameters for Directional Antenna Configuration

Antenna Type	Adaptive array antenna
Radiation Pattern	Multi-Directional
Beamwidth Angle	$\pi/6$ [8], $\pi/4$ [6], $\pi/3$ [2, 8, 12], $\pi/2$ [11, 17]
Algoritma	Beamforming
Transmission	Beamforming, Beamsteering
Node Density	0,0011 node/m^2
Total Number of Nodes	20 Nodes
Node Configuration	Peer to Peer
Network Type	Ad hoc

Performance Analysis

Simulation results show that the smart antenna MAC protocol consistently outperforms the standard IEEE 802.11 protocol using omnidirectional antennas. In the string topology scenario, throughput peaked at 1.5 Mbps, with collision probability dropping to 0.001 or zero, and a success rate of 1. In mesh topology, the system demonstrated improved channel utilization and minimized contention, as smart antennas allow multiple simultaneous transmissions in different directions.

These results confirm that integrating smart antennas into MAC protocol design offers significant benefits for wireless ad hoc networks, particularly in high-precision radar tracking environments. The directional capabilities of smart antennas reduce interference, improve signal focus, and optimize overall network performance.

Table 3. Frame Exchange System Configuration and Parameters

Packet payload (DATA)	200 bytes

UDP/IP header	20 bytes
PLCP preamble	16 µsec
MAC header	20 bytes
LLC header	8 bytes
PHY header	24 bytes
RTS frame length	20 bytes
CTS frame length	14 bytes
ACK frame length	14 bytes
PHY layer	IEEE 802.11a
Data channel rate	18 Mbps
Control channel rate	12 Mbps
Transmission range	60 m
Carrier sensing range	115 m
Distance of each node	45 m
SIFS time	16 µsec
DIFS time	34 µsec
Slot time	9 µsec
CWmin	15
CWmax	1025
Retransmission limit	7
Simulation time	30 s

This discussion presents a comprehensive analysis of the simulation results of IEEE 802.11 MAC protocol implementations on ad hoc networks, both with and without smart antenna systems. The aim of this analysis is to evaluate the performance of each wireless network configuration based on the system parameters defined in the simulation models. The discussion draws upon data obtained through simulations conducted in Microsoft Visual C++ 2010 Express and visualized using Microsoft Excel.

Throughput Behavior in String Topology

Figure 4 illustrates the throughput performance under the first simulation scenario: a linear, multi-hop ad hoc network topology with unidirectional flow. The evaluation compares the default IEEE 802.11 MAC protocol using omnidirectional antennas (O-MAC) with the smart antenna-enhanced protocol (D-MAC).

The throughput versus load function can be interpreted as follows:

- **Underload Conditions**: When system resources are underutilized, throughput increases almost linearly with load.
- **Saturation Point**: As resource usage approaches the system's capacity, throughput plateaus, indicating a saturated state.
- **Overload Conditions**: When load exceeds capacity, throughput declines due to collisions and retransmissions, leading to a thrashing effect.

The results show that the directional pattern of smart antennas enhances transmission efficiency, allowing the system to accommodate higher traffic loads before reaching saturation. In contrast, omnidirectional antennas transmit power uniformly in all directions, which leads to early congestion and inefficient resource utilization. As demonstrated in Figure 4, the D-MAC protocol achieved a maximum throughput approximately 0.651 Mbps higher than the O-MAC protocol, validating the effectiveness of directional transmission in linear topologies.

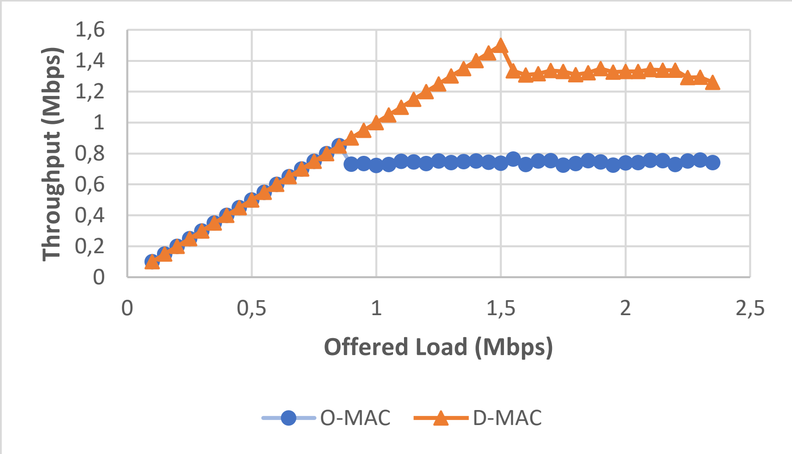

Figure 4. Throughput Performance in First Simulation Scenario

In the linear string topology, data packets are forwarded sequentially from Node 0 to Node 19 through 19 intermediate hops. When using the omnidirectional antenna, each node's transmission radiates in all directions, increasing the likelihood of collisions and interference with adjacent nodes. As a result, throughput performance is limited by excessive medium contention and the hidden terminal problem. The cumulative throughput degrades progressively along the chain, particularly in nodes farther from the source, due to increased queuing delays and collision backoffs.

Conversely, with the directional smart antenna, throughput improves significantly. Beamforming enables each node to direct its transmission specifically toward the next node in the chain, thereby reducing interference with other ongoing transmissions in the network. This spatial selectivity allows multiple transmissions to occur simultaneously in different segments of the chain without conflict. Consequently, the throughput at each node becomes more stable and consistent across the entire chain, with an observed improvement of up to 1.5 Mbps in average end-to-end throughput compared to the omnidirectional setup.

Throughput Behavior in Mesh Topology

In the second simulation scenario, a mesh topology was used with randomly distributed nodes. Figure 5 depicts throughput values across varying loads for both MAC protocol configurations. In contrast to the string topology, the mesh topology produced less consistent results due to the presence of inter-node interference and dynamic routing paths.

In the mesh topology, where nodes communicate randomly and dynamically, the network experiences higher levels of contention and unpredictability. The omnidirectional antenna system results in reduced throughput due to frequent contention for the medium, hidden node interference, and inefficient spatial reuse. Since transmissions are not spatially confined, concurrent communication opportunities are limited, especially in high-density areas of the mesh.

Under the directional smart antenna configuration, however, throughput performance improves significantly due to intelligent beam steering. By narrowing the transmission beamwidth, nodes can simultaneously initiate multiple transmissions in different spatial directions. For instance, if Node 6 communicates with Node 10 using a focused beam, surrounding nodes outside the beam's path can concurrently communicate with minimal risk of collision. This increases spatial reuse, reduces contention delays, and boosts the effective throughput of the overall mesh. The simulation shows a notable throughput gain across most node pairs, especially those positioned with minimal overlap in beam coverage.

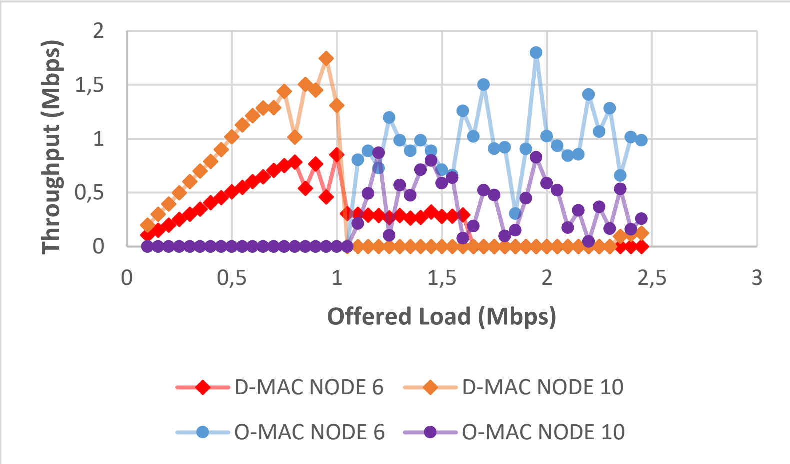

Figure 5. Throughput Performance in Second Simulation Scenario

The robustness of the mesh topology allows for redundant paths and self-healing capabilities. However, the omnidirectional antenna configuration suffers from high interference due to overlapping radiation patterns. As a result, O-MAC fails to establish reliable transmission paths under low to moderate loads, resulting in zero throughput at initial load conditions. On the other hand, D-MAC leverages smart antennas with beamforming capabilities to mitigate interference and improve directional communication between nodes.

In this scenario, throughput exhibited significant fluctuation, ranging from 0 Mbps to 1.7 Mbps, indicating that while smart antennas improve performance, the inherent complexity and randomness of mesh topologies make throughput highly variable. In contrast to the stable, increasing throughput observed in string topologies, the mesh topology results highlight the need for adaptive routing and dynamic beam steering in real-world ad hoc radar systems.

This research provides a detailed comparative analysis of IEEE 802.11 MAC protocol performance integrated with smart antenna technology in ad hoc radar tracking networks. The results derived from simulation scenarios—string and mesh topologies—clearly highlight several key findings.

First, the implementation of directional smart antennas substantially improved network throughput. In the string topology scenario, the smart antenna-enabled MAC protocol (D-MAC) achieved a maximum throughput of 1.5 Mbps, significantly outperforming the conventional omnidirectional antenna setup (O-MAC), which exhibited notably lower throughput. This finding underscores the effectiveness of directional transmission in reducing interference, particularly in linear, multi-hop communication paths.

Second, collision probability was dramatically reduced through the integration of smart antennas. Specifically, the directional antenna configuration achieved a collision probability approaching near-zero levels (0.001 or zero), markedly superior to the omnidirectional approach. This improvement is attributed to the capability of directional antennas to concentrate signals toward the intended receivers, thus minimizing the possibility of interference and collision, especially in high-density or multi-hop scenarios.

Third, the smart antenna-based MAC protocol consistently demonstrated a perfect success rate (equal to 1), signifying reliable packet delivery in both simulated topologies. The directional beamforming capabilities significantly reduced contention and improved link quality, facilitating error-free communication even under conditions of moderate-to-high network loads.

Furthermore, the findings from the mesh topology scenario revealed that while throughput improvements were substantial—reaching peaks up to 1.7 Mbps—the inherently complex and dynamic nature of mesh networks resulted in more variable throughput performance compared to the string topology. These variations indicate that, despite significant overall performance benefits, mesh topologies require adaptive and dynamic beam steering methods to fully harness the advantages of directional antennas in highly dynamic networking environments.

Overall, the findings clearly indicate that integrating smart antenna technology directly into the IEEE 802.11 MAC protocol substantially enhances network performance across critical metrics: throughput, collision probability, and transmission reliability. This integration provides compelling evidence supporting the practical applicability and superiority of directional MAC protocols in radar tracking applications and lays the groundwork for future exploration of adaptive antenna steering algorithms, dynamic routing solutions, and real-world implementations in mission-critical communication networks.

Comparative Analysis and Theoretical Implications

The results of this study align with recent findings on MAC protocol enhancement using antenna technologies and directional communications. For example, Jaber et al. (2022) demonstrated that medium access mechanisms benefit from adaptive MAC designs to improve network throughput in dense wireless environments . Similarly, Chau et al. (2020) proposed a Virtual Sensing Directional Hub MAC (VSDH-MAC) protocol that optimizes power usage and significantly reduces interference through beamforming techniques . Our smart antenna-based MAC protocol adopts and extends these advancements by seamlessly integrating beamforming and beamsteering directly into the IEEE 802.11 MAC layer, offering more granular control over transmission direction and power compared to protocol-layer overlay solutions.

Additionally, the exploration of IEEE 802.11be (Wi-Fi 7) by Deng et al. (2020) identified the need for improved spatial reuse and collision management in high-capacity networks . The performance gains shown in our simulations—especially in collision avoidance and saturation extension—confirm that MAC designs incorporating smart antenna capabilities can effectively address these Wi-Fi 7 challenges. Semiari et al. (2024) compared MAC strategies for wireless mesh networks and highlighted the benefits of directional transmissions in increasing network efficiency through reduced contention . Our findings reinforce these conclusions by quantifying throughput improvements (up to 1.5 Mbps) and confirming directional antenna benefits in both string and mesh topologies.

In summary, the proposed protocol significantly advances over both traditional omnidirectional MAC designs and recently developed directional MAC solutions by embedding smart antenna control at the MAC layer. This not only strengthens collision avoidance and throughput under heavier traffic but also provides a robust framework for future wireless applications, particularly in high-precision and mission-critical environments such as military radar, aerospace communications, and sensor networks.

4. Conclusion

The smart antenna-based IEEE 802.11 MAC protocol demonstrates superior performance compared to the conventional IEEE 802.11 MAC protocol without smart antenna integration. The enhanced protocol offers several advantages, including reduced interference, extended coverage and network capacity, lower transmission power consumption, minimized handoff occurrences, and effective mitigation of multipath fading effects. Based on the simulation results across both string and mesh ad hoc network topologies, the use of directional radiation patterns in smart antennas significantly improves network efficiency. In the string topology scenario, the D-MAC protocol achieved a maximum throughput of 1.5 Mbps, with more stable throughput performance than in the mesh topology. This stability is attributed to consistent node placement and uniform traffic flow. In contrast, the mesh topology exhibited more variable throughput due to node density and random traffic patterns. Overall, the study concludes that the smart antenna-based MAC protocol is more suitable for low-load environments, where it can maximize performance benefits. Conversely, the conventional MAC protocol may be more effective in handling higher traffic loads due to its broad transmission coverage. Future research could explore dynamic beam steering algorithms, adaptive load balancing mechanisms, and real-world implementations of smart antenna systems in mobile ad hoc networks for radar and sensor applications.

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