A Novel Guard Zone Based Multiple Access Protocol for Autonomous D2D Cellular Communication

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In today's interconnected and digitally driven era, Device-to-Device (D2D) communication has emerged as a transformative paradigm, enabling direct and efficient interactions between nearby devices with or without traditional network infrastructure. This research introduces a novel communication protocol that autonomously facilitates D2D communication in network-constrained environments, maximizing node engagement and ensuring reliable data transmission while addressing the inherent challenges faced by existing Medium Access Control (MAC) protocols, such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The study specifically focuses on developing a protocol that enables real-time information sharing among neighboring nodes without network assistance. To evaluate the protocol's performance, comprehensive simulations were conducted using MATLAB, assessing its effectiveness in increasing the number of active nodes and reducing collision probability. The results demonstrate that the proposed protocol significantly decreases interference while enhancing data throughput and energy efficiency, achieving a 15% increase in active node pairs and a notable 4% reduction in collision probability. By minimizing contention overhead and optimizing data transmission, the protocol effectively lowers latency, ensuring reliable communication in environments lacking network support. Furthermore, it conserves energy by reducing idle listening, thereby extending battery life and promoting sustainable wireless communication systems. This research provides a robust solution to enhance D2D communication in isolated environments, paving the way for more resilient wireless ecosystems.

Keywords: D2D Communication; MAC Protocols; Guard Zone; Network Un-Assisted; Autonomous.

Introduction:

The implementation of Device-to-Device (D2D) communication in network-constrained environments presents several critical challenges that current Medium Access Control (MAC) protocols fail to adequately address. These challenges include high contention overhead, increased collision rates, and inefficient power consumption due to idle listening [1][2]. In the absence of a reliable network infrastructure, these issues significantly hinder the performance and efficiency of D2D communication systems [3][4]. To overcome these obstacles, there is a need for a novel communication protocol specifically designed to function autonomously without network support. This research aims to develop such a protocol to enhance data transmission efficiency, reduce latency, and conserve energy by minimizing idle listening. By facilitating real-time information sharing among neighboring nodes, the proposed protocol seeks to optimize the overall performance and sustainability of D2D communication systems. This study will explore the technical details of the new protocol and evaluate its effectiveness in improving network resilience, resource utilization, and connectivity within evolving wireless ecosystems.

Interference management strategies in D2D communication have been a focal point of research, aimed at optimizing resource allocation and enhancing overall network performance. Various techniques and protocols have been proposed to address challenges such as interference mitigation, synchronization requirements, and resource allocation complexities. Guard zone strategies, which define thresholds for Signal-to-Interference Plus-Noise Ratio (SINR), have been explored to manage interference in D2D communication [5]. However, existing approaches often lack optimal resource management and overlook Quality of Service (QoS) considerations. Synchronization requirements present a challenge in effectively managing interference, necessitating careful coordination in each D2D scenario [6].

Game-theoretic resource allocation methods have been investigated for D2D Local Area Networks (LANs) and direct D2D communication in [7], deploying a strategic decision-making framework to allocate resources efficiently among competing users. However, centralizing resource allocation through e-Node B or base stations introduces high computational complexity [8] and fails to provide solutions when the base station is unavailable. Similarly, an SDN-based protocol has been proposed, leveraging SDN controllers for resource allocation assistance in [9], offering a flexible and programmable network architecture. An auction-based solution has also been proposed, facilitating efficient resource allocation in a distributed manner involving e-NBs or base stations as auctioneers [10]. While this method decentralizes the allocation process, it still relies on central entities for coordination.

Past research efforts have predominantly focused on centralized or complex resource allocation methodologies rather than distributed approaches without centralized entity involvement. Guard zone concepts have been explored in ad hoc networks, but clear techniques for transmitter-receiver handshake processes remain elusive [11]. The implementation of a Request-to-Send/Clear-to-Send (RTS/CTS) method with a timer necessitates synchronization, underscoring the challenges of synchronization in interference management [16]. The CSMA (Carrier Sense Multiple Access) protocol, part of IEEE 802.11 [12][13], incorporates carrier sensing to detect channel activity before transmitting and employs a Collision Avoidance (CA) mechanism with a back-off delay to avoid simultaneous transmissions and reduce collisions. However, CSMA/CA is susceptible to interference and collisions in D2D scenarios, particularly as the number of devices increases [14]. Contention overhead in CSMA, due to idle listening and back-off intervals, can significantly impact D2D communication efficiency, leading to reduced throughput and increased latency as device density rises [1]. Following the introduction, the "Methodology and Implementation" section details the proposed protocol and the analysis techniques used. The "Results and Discussion" section presents findings through comparative analysis. The "Conclusion" synthesizes key insights, implications, and future research directions. Lastly, the "References" section lists all cited works, ensuring proper attribution.

This research introduces a novel communication protocol specifically designed for Device-to-Device (D2D) communication in network-unassisted environments (Figure 2). The primary contribution of this study lies in the development of a protocol that enhances data transmission efficiency, reduces power consumption, and improves network capacity and collision management.

The objective of the Study:

The objective of this research is to develop a novel communication protocol for Device-to-Device (D2D) communication in environments lacking network assistance. The aim is to enhance data transmission efficiency, reduce latency, optimize energy consumption, increase network capacity, and minimize collision probability.

Novelty Statement:

This research presents a novel Device-to-Device (D2D) communication protocol that autonomously operates in network-constrained environments. It addresses the inefficiencies of existing Medium Access Control (MAC) protocols by facilitating real-time information sharing among neighboring nodes. The protocol significantly reduces idle listening, minimizes contention, and lowers power consumption. The flow of the study is illustrated in Figure 1.

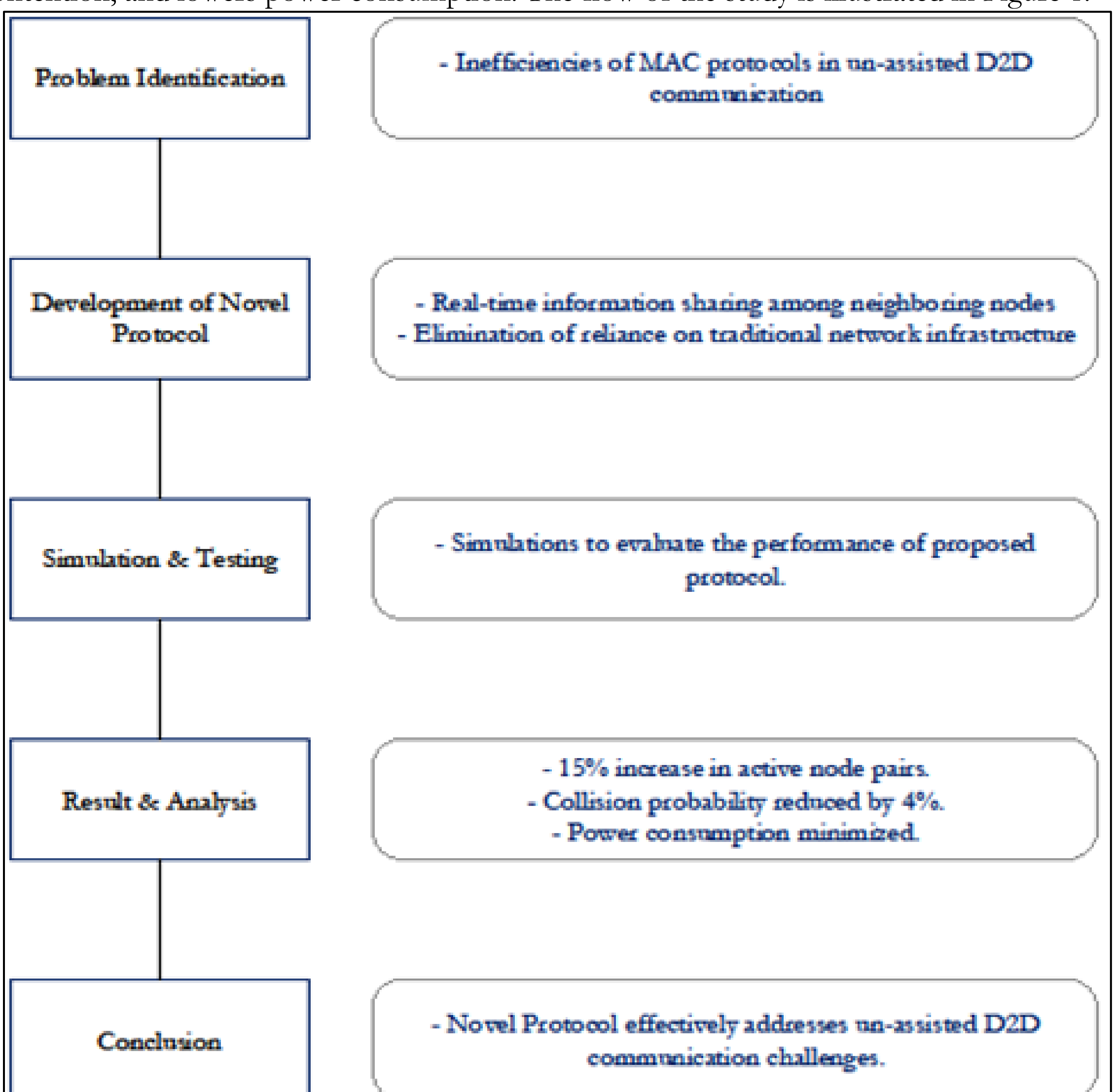

Figure 1. Flow of Study Diagram

Methodology and Implementation:

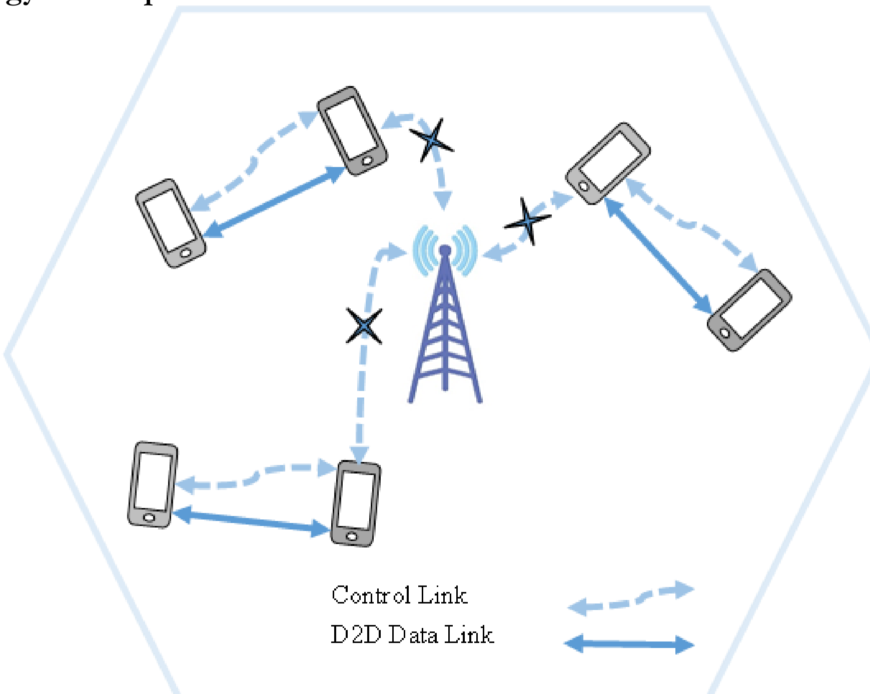

Figure 2. No assistance by centralized network (BS)

To analyze the performance of Device-to-Device (D2D) communication, this study employs a homogeneous Poisson Point Process (PPP) network model, with the effects of shadowing inherently captured in the signal strength [15]. D2D transmitters and receivers are randomly distributed with a density of λD2D on a two-dimensional plane, and each transmitter is paired with a receiver, separated by a constant distance d. The network comprises D2D transmitters and receivers that are randomly allocated on the plane, with each D2D node granted exclusive network bandwidth to eliminate cross-mode interference. The primary focus is on the unicast transmission of D2D nodes within the transmission range of a D2D transmitter. Multicast communication is considered only for exchanging control-related information, such as location and spectrum occupancy. While power optimization is outside the scope of this work, each D2D transmitter node operates at its maximum power level, denoted as $Pmax$. The optimization problem can be formulated as follows:

$$Max\ |z| \qquad (1)$$

$$s.t \quad \mathrm{SINR_z} \geq \frac{\beta_i}{SF}, \qquad \leq N$$

Where: z represents the number of active nodes within a specific time duration, and \(N \) denotes the total number of nodes in the system. The primary objective is to ensure reliable D2D communication by maximizing the number of active nodes while satisfying the Signal-to-Interference-plus-Noise Ratio (SINR) requirements. The SINR condition for the ith D2D receiver must be fulfilled for all N nodes:

$$\mathrm{SINR_i}\ (\mathbf{P}) = \frac{P_i G_{ii}}{\sum_{j\neq i}\ (P_j G_{ij}) + (SF)n_i} \geq \frac{\beta_i}{SF}, \forall i = 1, 2, \qquad (2)$$

Where SF represents the spreading gain. All nodes transmit with maximum power Pmax. The path loss is given by $G_{ij} = (\frac{1}{r_{ij}})^{\alpha}$, is the path loss exponent α and r_{ij} is the distance between the j_{th} interfering transmitter and the i_{th} receiver. β_i denotes the minimum SINR required for successful communication on the i_{th} D2D link. In the proposed protocol, an efficient and controlled communication mechanism is established to facilitate data transmission. When a transmitter (Tx) intends to send data, it is uniquely aware of its permission status, which determines whether it can initiate transmission. This awareness enables the transmitter to make informed decisions regarding its transmission. Additionally, the critical interference radius r_{ci} [14] is considered a guard zone within which any single interferer can cause an outage at the receiver.

$$r_{ci} = dji\left(\frac{\beta_i}{SF}\right)^{\frac{1}{\alpha}} \quad (3)$$

Where, d_{ji} denotes distance between the active Tx-Rx pair and while α is the path loss exponent.

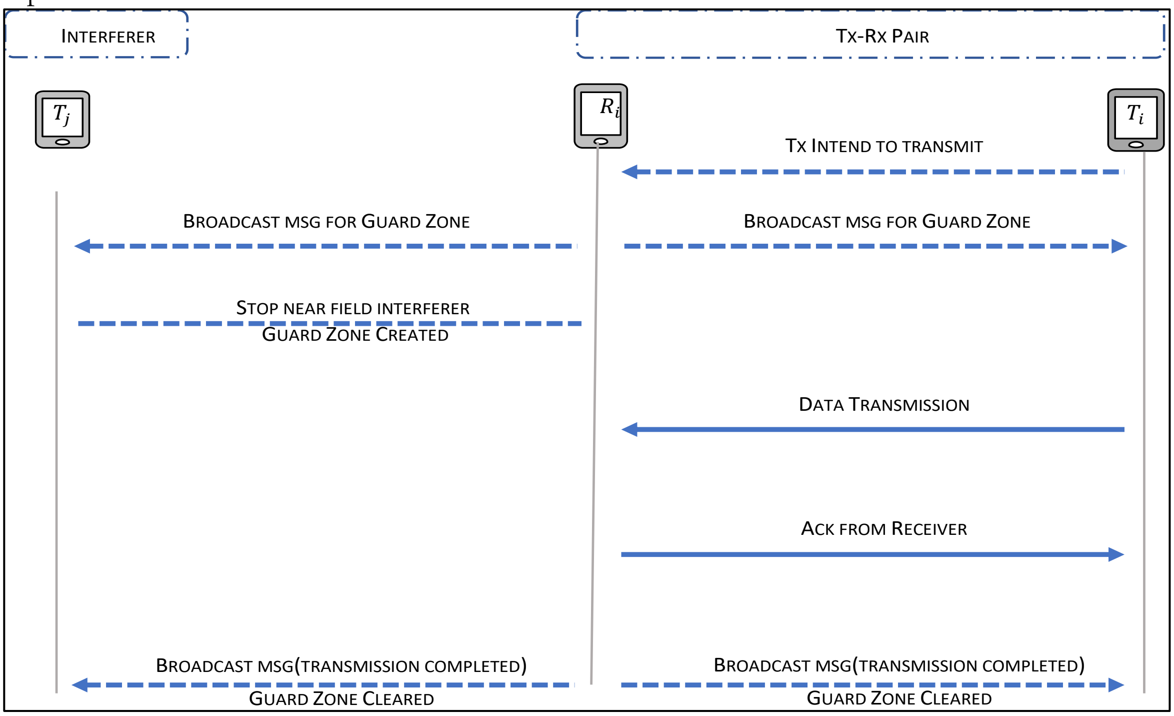

Figure 2. GZMAP Flow, considering one Tx-Rx Pair and one interferer

In our case, SF is equal to β, which makes the critical radius equivalent to the transmission radius. To initiate data transmission, the transmitter Tx proactively notifies the associated receiver Rx of its intent to transmit. This direct notification serves as a clear indication of the Tx's readiness to commence data transfer. Upon receiving this notification, the Rx actively engages in the communication process and verifies the channel state. Subsequently, the Rx broadcasts a specialized message to all nodes within a designated guard zone. The guard zone (3) is meticulously defined as an area surrounding the Rx, within which other devices must adhere to communication rules; any single node in this area can potentially cause an outage at the receiver. This unique broadcast message contains explicit instructions for the entities within the guard zone, mandating them not to transmit data or cause interference while the Rx's transmission is underway. By issuing such clear instructions, the proposed system establishes an environment of control during the transmission process. The guard zone ensures that all participating nodes comply with the specified communication protocol, thereby preventing potential collisions, disruptions, or interference that could compromise the quality and reliability of data transmission. In edge cases where multiple nodes attempt to transmit simultaneously, the Guard Zone rule (3) of the protocol will determine whether to permit the transmissions. Figure 4 illustrates the flow of the GZMAP algorithm.

```
% This Algorithm is focused on single frequency resource; for multiple resources same is to be executed;
N : Number of D2D nodes in the network;
Gx : Guard zone around receiver;
for Transmission Intended D2D pair(Already Aware of Channel status within Guard zone) do
    if channel=idle on Both Rx and Tx then
        Broadcast message for guard zone
        Create Gx;
        % Stopping Near-field interferers to to transmit around Rx;
        for Transmission do
            Transmission started;
            % Wait for transmission to complete;
            if Ack=1 then
                break;
                % exit transmission loop;
            end
        end
    end
    Clear Gx;
end
```

Algorithm 1: Guard Zone based Multiple Access Protocol (GZMAP)

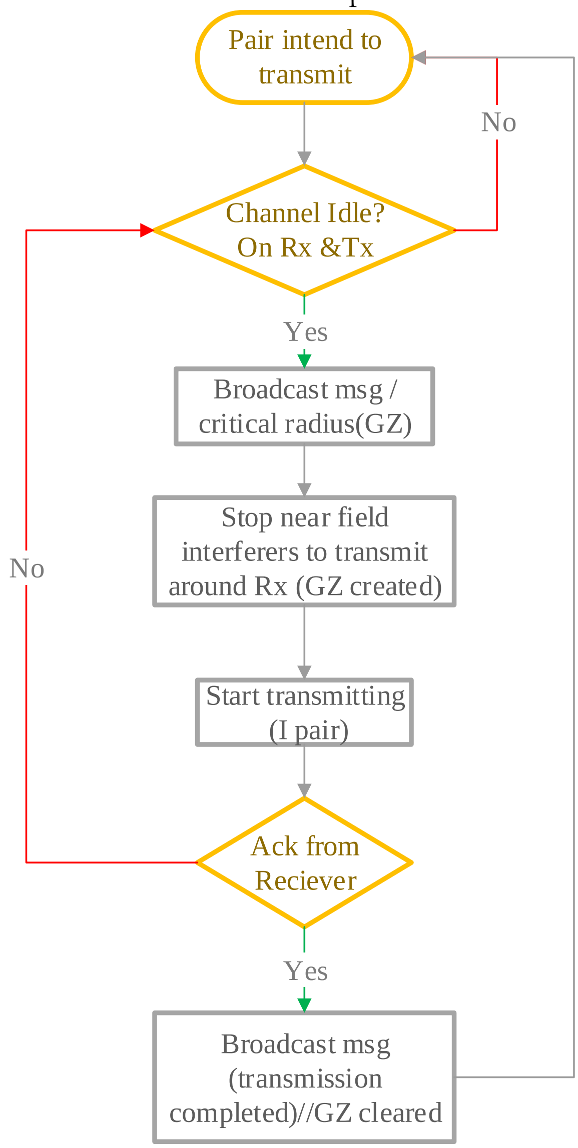

Figure 3. Flow of GZMAP

Result and Discussion:

We will now proceed with a comparative analysis of the Carrier Sense Multiple Access (CSMA) protocol and the Guard Zone-based Medium Access Protocol (GZMAP) under various conditions. The improvements in performance between CSMA and GZMAP are discussed below:

Collision Avoidance Mechanism:

- **CSMA/CA**: As mentioned earlier, CSMA/CA relies on a contention window, which is a variable time period during which nodes wait and back off to prevent collisions during channel access.
- **GZMAP:** In contrast, GZMAP implements a proactive guard zone mechanism that significantly lowers the likelihood of collisions by regulating transmissions within a designated spatial radius. This approach not only minimizes contention overhead but also enhances spectral efficiency.

Efficiency in Channel Utilization:

- **CSMA/CA:** Although CSMA/CA effectively avoids collisions, it can result in idle listening and inefficient channel utilization, especially in densely populated networks.
- **GZMAP:** GZMAP optimizes channel utilization by dynamically adjusting guard zones in response to real-time communication patterns. This adaptability enhances spectral efficiency and minimizes idle listening, ultimately resulting in higher throughput.

Latency and Throughput Performance:

- **CSMA/CA:** The contention resolution mechanisms in CSMA/CA can lead to variable latency, which may adversely affect the performance of real-time applications.
- **GZMAP:** GZMAP's controlled communication mechanism effectively minimizes latency spikes by prioritizing transmissions within guard zones. This prioritization enhances throughput and effectively supports time-sensitive applications.

Handling Network Congestion:

- **CSMA/CA:** Under high network loads, the contention window mechanism of CSMA/CA can result in increased collisions and a decline in network performance.
- **GZMAP:** GZMAP alleviates congestion by employing adaptive guard zone management, which dynamically allocates resources to reduce contention and ensure efficient data flow.

Energy Efficiency:

- **CSMA/CA:** Frequent channel sensing and backoff procedures in CSMA/CA can lead to excessive energy consumption.
- **GZMAP:** GZMAP improves energy efficiency by minimizing idle listening and reducing contention-related energy waste, thereby optimizing resource utilization and enhancing overall network sustainability.

Scalability and Adaptability:

- **CSMA/CA:** CSMA/CA's performance may degrade in large-scale networks with diverse traffic types.
- **GZMAP:** GZMAP demonstrates scalability and adaptability through dynamic guard zone management, making it well-suited for diverse network environments, including IoT deployments and dynamic mobile networks. Except for a few parameters, the system specifications are aligned with those outlined by 3GPP in their technical document [17], as summarized in Table 1.

Computation Complexity:

No Collision Case: The first scenario considers a sequential entry of transmitters into the system, eliminating the possibility of collisions. If a transmitter detects channel activity, it refrains from transmitting and waits for the contention window. In contrast, GZMAP actively shares control information; whenever a transmitter intends to begin or conclude a transmission, its corresponding receiver broadcasts a message to prevent unnecessary resource wastage. As illustrated in Figure 5, when the collision probability is zero, it significantly influences the number of active nodes in the CSMA/CA system due to the contention window.

Table 1. Simulation Parameters

Parameters	Value
Transmission Radius	20m
Required SINR	10dB
Resource Block	1
Radius of cell	500m
Total D2D pair	140 & 700
Max Transmission power	23dBm
Path loss exponent	4,5,6

Note: SF is equal to β which makes the critical radius equal to transmission radius (3).

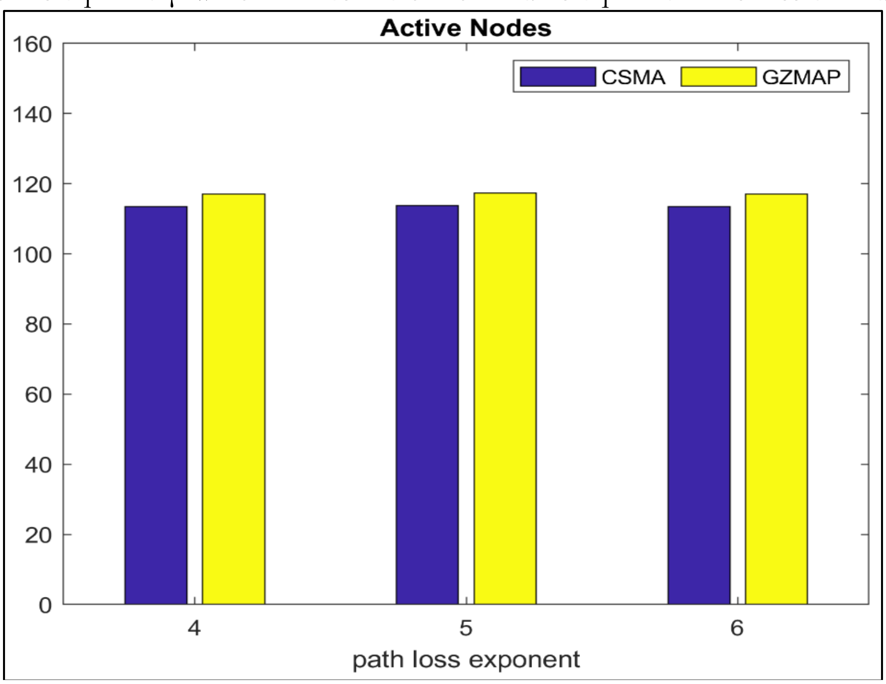

Figure 4. No Collision Case Collision Case:

The second scenario assumes that all nodes broadcast simultaneously, resulting in the highest collision rate under the Carrier Sense Multiple Access (CSMA) protocol. In contrast, GZMAP facilitates the sharing of control information over a reliable channel, enabling the receiver to possess prior knowledge of the channel status, thus preventing collisions. This proactive approach gives GZMAP a significant competitive advantage over CSMA.

Random Transmission Case:

In this third scenario, transmitters operate randomly, leading to idle listening and contention windows in CSMA/CA. In contrast, GZMAP utilizes broadcast messages to inform nodes of ongoing transmissions, thereby eliminating the need for idle listening and contention windows. Figure 6 compares CSMA/CA and GZMAP over 1,000 iterations. The graph indicates that while the number of active nodes is similar between CSMA and GZMAP, GZMAP demonstrates superior performance in reducing collision probability.

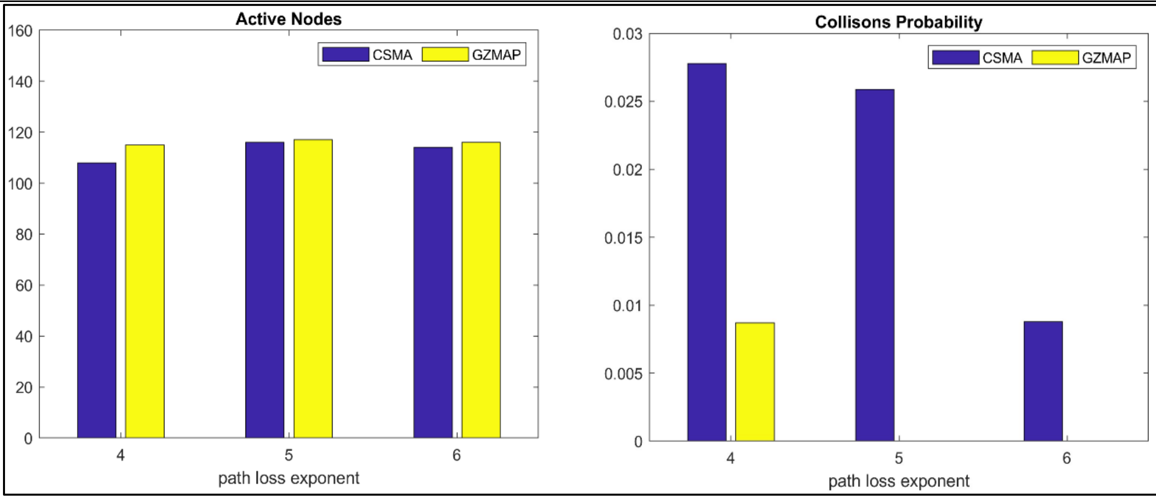

Figure 5. Random Transmission case

In Figure 7, the Path loss exponent is fixed while the number of nodes are being varied and it can be seen from the graph that a greater number of nodes can be accommodated in GZMAP with less collision probability.

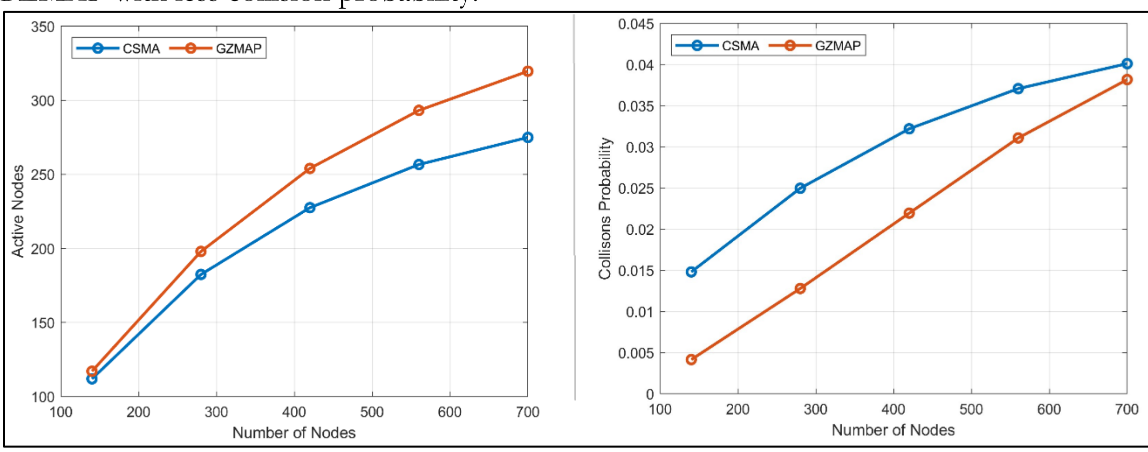

Figure 6. For path loss exponent=5, nodes being increased

Conclusion:

In this comprehensive research, we introduced the Guard Zone-based Multiple Access Protocol (GZMAP) as a groundbreaking approach to enhancing Device-to-Device (D2D) communication within wireless networks. GZMAP was developed to address the inherent limitations of traditional protocols, such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), specifically targeting issues related to contention overhead and idle listening. By implementing a controlled communication mechanism, GZMAP optimizes resource utilization among devices, resulting in significant improvements in network performance, reduced latency, and increased throughput.

Through rigorous simulations and analyses across various scenarios, we conducted a comparative study of CSMA/CA and GZMAP. Our findings conclusively demonstrate GZMAP's superior performance, whether in collision-free environments or in scenarios characterized by random transmission patterns. GZMAP's capacity to significantly reduce collision probabilities, eliminate idle listening, and obviate the need for contention windows highlights its effectiveness in enhancing the overall efficiency of D2D communication.

A pivotal insight from this research is the crucial role of optimized resource allocation in D2D communication networks. GZMAP exemplifies how a well-designed protocol can elevate network performance and quality of service metrics. By streamlining communication processes and minimizing resource wastage, GZMAP sets a new standard for efficient and reliable D2D communication protocols. The practical implications of GZMAP are profound, providing a scalable solution to the challenges encountered in D2D communication environments. Its potential for seamless integration into existing wireless D2D networks makes it a valuable asset for network operators and service providers aiming to enhance communication efficiency and user experience.

However, this study acknowledges the exclusion of power optimization, an important consideration for real-world applications. Future research should explore power optimization techniques and evaluate GZMAP against established standards, such as the IEEE 802 series. In conclusion, this research significantly advances Device-to-Device (D2D) technology, paving the way for future innovations in wireless communication protocols. GZMAP represents a promising pathway for further exploration and implementation in wireless D2D networks, aligning with the increasing demand for seamless, reliable, and efficient communication solutions in modern wireless ecosystems.

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Author's Contribution: Moazzam carried out Writing-original draft, Data curation, conceptualization, methodology, investigation, formal analysis, validation, and project administration. Jehan Zeb supervised the research, and conceptualization and reviewed the paper.

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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