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Detection of Nodes Cloning and Attacks in Wireless Sensor Networks and Their Possible Solution

Raajaiswar Agnihatri,
M.Tech Scholar, Department of Computer Science and Engineering Faculty of Engineering, JBIT, Dehradun, Uk

Raajvidyaa Agnihotri,
MCA, PGDCA, Graduate from University of Delhi, Delhi, India

Dr. Farhad Alam,
Associate Professor, Department of Computer Science and Engineering Faculty of Engineering, JBIT, Dehradun, Uk

***Abstract*— As the capabilities of computing and communication technologies continue to advance, WSNs are increasingly vital in overcoming challenges and enhancing reliability across various applications. WSNs play a very important role in supervising and transferring information from remote or inaccessible locations, contributing to improved efficiency and reduced obstacles in Earth's diverse environments. WSNs face numerous security threats, including eavesdropping, intrusions, packet tampering, and device specific attacks. Despite the efficacy of cryptographic techniques and key management protocols in addressing many of these threats, certain vulnerabilities, such as sensing unit replication attacks or node clone attacks, remain particularly challenging. In sensing unit replication attacks, some sensing units are physically captured and reprogrammed, replicated as clones of already existing legitimate sensing units, and injected back into WSN—but now obey the intruder's commands to cripple the system or take over the network. The presence of cloned sensing units can facilitate further attacks, such as Sybil attacks where targeted data suppression occurs, in which a malicious sensing unit intentionally discards or modifies specific data pieces, while forwarding data to other sensing units in the system, leading to misinformation and potential system failures. This paper addresses these challenges by analyzing and evaluating feasible Decentralized Mechanisms and strategies specifically designed to successfully detect sensing unit replication threats in WSNs, stressing the need for mechanism to be energy- and memory-efficient and capable of operating under limited computational resources, as sensor networks are constrained in these and many other resources when deployed for Environmental and Surveillance Projects in remote geographical areas. Moreover, this work reviews vital and essential elements of WSNs, covering major application areas, information fusion methods, and commonly encountered security challenges. The findings and knowledge presented strive to enhance reliable, robust, self-organized, scalable, and efficient WSNs with high intrusion detection capabilities—vital for shaping the future of safe and efficient Networks for life-saving critical projects, even in unpredictable environments in far-flung areas.**

***Keywords*—Wireless Sensor Networks (WSNs), Sensor node (sensing unit, sensor), Clone detection (replica detection, replicated node), Randomized witness selection, Randomized Secure Detection (RSD) Protocol, Sensing Unit Replication Attacks, Decentralized Detection Mechanism, Energy-Efficient Protocols, Security in WSN, Intrusion Detection in WSNs, Resource-Constrained Networks, IoT-integrated WSN Security.**

INTRODUCTION

WSNs are applied in areas critical to the sustainability of environments, technological advancements, and social development. In environmental monitoring, they help in tracking air pollution, water quality, detecting forest fires, managing natural disasters, and providing real-time data for in-time interventions [1],[2]. In agriculture, they monitor crop health, soil moisture, and temperature to increase farm yield and conserve resources [3]. In healthcare, they aid in improving diagnosis and continuous patient monitoring [4]. In the military, WSNs are used for various types of surveillance and reporting [5]. In societal development, they are applied in smart city infrastructure, traffic management, and public safety systems [6]. Within Industrial systems, WSNs enable process automation, alarm systems, and safety measures [7].

WSNs are vital in these areas because of their ability to monitor and report in real time without human presence or intervention. This helps in faster decision making, increase safety and very much reduce operational costs. In all these areas they are and can provide real time data, early warnings, predictive maintenance, alarms, surveillance and human monitoring [8].

In this paper, the terms sensing unit, sensor, and node are used interchangeably to refer to a WSN device capable of sensing, processing, and communication. Likewise, the terms clone, replica, and replicated node are used synonymously to describe a maliciously inserted copy of a legitimate node within the network [9].

WSNs consist of many low power sensing units spread or arranged in a desired and distributed architecture, where every sensing unit does sensing, processing and communication. These sensing units communicate wirelessly and mostly use multi-hop routing to send and receive data to a Base station (BS) or centralized sink. The layered protocol stack, energy-aware MAC and routing layers makes resource utilization efficient and robust systems [10]. Additionally modularity of WSNs allows for integration with any external networks, cloud

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systems or IoT systems, making WSNs highly flexible and suitable for above discussed areas [11].

Despite their advantages, WSNs face several challenges that impact their performance and security such as limited energy, low processing power, and constrained memory [12]. Their deployment in remote or harsh environments makes them vulnerable to signal interference, physical tampering, and attacks like sensing unit replication or denial-of-service. Their decentralized nature and wireless communication further complicate security and scalability. As a result, making WSNs reliable and scalable by developing WSN protocols and mechanisms has drawn considerable focus in recent research and has gained interest among researchers, the IT industry, technology manufacturers and sectors where WSNs are applied [13].

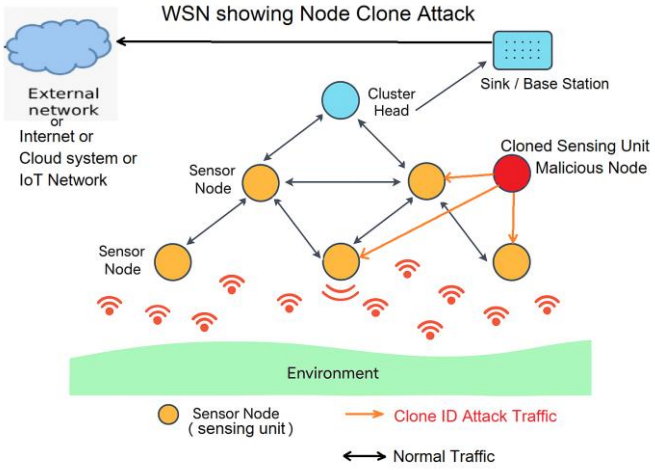

Figure 1: Wireless Sensor Network (WSN) showing node clone attack.

Normal communication and malicious clone ID traffic are shown, highlighting how a replicated (cloned) node disrupts data flow within the sensor network.

This paper opens with an overview of WSNs architecture, highlighting its fundamental elements and how they interact. Then it proceeds to examine the unique characteristics of WSNs, followed by a comprehensive analysis of the RSD protocol as a potential solution for detecting sensing unit replications and enhancing WSN security. In conclusion, the paper identifies critical research challenges and unresolved problems that need to be addressed and solved to build trust worthy WSNs using efficient and affordable WSN protocols and mechanisms.

The remainder of this article is organized as follows: Section 2 provides a detailed overview of WSN architecture; Section 3 outlines the key application areas of WSNs; Section 4 examines the security and privacy issues inherent in WSNs; Section 5 explores the Architecture, Operational design, and Advantages of the Proposed RSD protocol and its integration within WSNs; Section 6 presents a Performance Analysis and Comparative Discussion of RSD against other existing protocols and technologies. The subsequent sections identify critical research gaps and outline potential future enhancements.

LITERATURE REVIEW

WSNs have become integral to domains ranging from environmental monitoring to military surveillance. However, their open deployment in remote or harsh environments and limited resources available at each sensing unit make them vulnerable to security threats, particularly sensing unit replication attacks. In such attacks, intruder replicate legitimate sensing units and inject replicas into the network, disrupting communication, compromising data integrity, or facilitating larger intrusions [14],[15]. The detection of replicated sensing units, especially in large-scale or resource-constrained environments, remains a challenging task [16].

Initial research focused on centralized detection mechanisms, where base stations authenticated sensing unit's identities and locations. These methods proved effective in small-scale networks but suffered from scalability limitations and presented single points of failure [17]. As WSNs grew more dynamic and decentralized, researchers proposed distributed techniques such as SET (Simple Energy-efficient Trust) and Random Key Predistribution, which reduced central dependency but often struggled to balance energy efficiency with detection accuracy [18],[19]. Among randomized approaches, the red protocol introduced the idea of forwarding identity claims to randomly selected witness sensing units to increase detection unpredictability. While influential, red was limited in hostile environments involving collusion or partitioned communication [15]. More sophisticated solutions—such as those using mobile agents, location-aware detection, or machine learning algorithms—improved replica detection performance, but often incurred high computational and energy costs, making them unsuitable for typical WSN deployments [9],[22],[23].

Recent work has explored blockchain-integrated frameworks for clone detection, providing secure, tamper-resistant verification through distributed ledgers. However, such systems remain largely conceptual due to the resource constraints of sensor hardware and the complexity of blockchain infrastructure [24],[25]. In response to these ongoing challenges, the proposed Randomized Secure Detection (RSD) protocol has been developed as a lightweight and practical solution for clone detection in static WSNs. RSD employs random witness routing, adaptive claim broadcasting, and a secure alert mechanism without depending on heavy cryptographic operations or centralized control. Unlike prior approaches, RSD is designed specifically to address the energy and scalability limitations common in real-world WSN deployments. Its architecture prioritizes efficiency, robustness, and ease of integration, making it a promising candidate for deployment in mission-critical WSNs.

Although substantial milestones are achieved but several issues still remain like mobility support, resilience against collusion attacks, real-time responsiveness, and integration with broader IoT or blockchain based infrastructures continue to represent still ongoing research challenges. This literature review highlights the evolving and interdisciplinary nature of clone

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detection in WSNs, reinforcing the need for holistic approaches that blend lightweight security protocols, decentralized trust mechanisms, and adaptive detection strategies to build scalable, secure, and energy-efficient wireless sensor systems.

2. WSN ARCHITECTURE

The architecture of WSNs forms the foundation and framework that governs and decides the interaction among sensing units, communication protocols, and data collection mechanisms. A clear understanding of the components and structure of WSNs is essential for developing efficient and scalable security mechanisms, such as clone detection protocols. The WSN architecture considered in this research aligns with internationally recognized standards, including IEEE 1451 for sensor interfaces, IEEE 802.15.4 for physical and MAC layers, and RFC 6550 (RPL) for multi-hop routing in low-power lossy networks [26],[27],[28]. The following subsections provide a systematic overview of key architectural components, communication types, and defining characteristics of WSNs.

2.1 Main Components

Based on widely adopted WSN design principles and reference models, the architecture can be logically divided into three primary layers:

• Sensing Unit Layer / Sensors Layer:
This layer comprises a large number of low-power, resource-constrained sensing units deployed across the monitoring area. These sensing units are equipped with microsensors, microcontrollers, memory, and wireless communication interfaces. Each sensing unit performs local sensing (e.g., temperature, humidity, and motion), minimal processing, and data forwarding. The sensing units are typically static and deployed either randomly or in a grid pattern, depending on the application [7].

• Sink/Base Station Layer:
This layer includes one or more sink nodes or base stations (BS) that serve as central collection points for data forwarded from the sensing units. BS generally has higher energy capacity and computational power as compared to sensing units [28]. BS may be connected to a local server, gateway, or cloud platform, and are responsible for aggregating data, passing alerts, and providing remote access to the WSN [1].

• External Network Layer:
This layer represents the broader network environment with which the WSN interacts. It includes cloud services, monitoring centers, or third-party applications connected to the BS. This domain enables integration with external security tools, storage systems, or real-time dashboards for decision-making and control [31].
Figure 1 shows a typical WSN setup with distributed sensing units, multi-hop communication, and a centralized sink node, along with a visual representation of a node clone attack.

2.2 Deployment and Communication Structure

The WSN architecture considered in this research follows a static, homogeneous, multi-hop model. Sensing Units are uniformly distributed over the area under surveillance and communicate using short-range wireless transmissions. Sensing Units use multi-hop routing to forward sensed data to the sink BS, as direct communication may not be possible due to energy or range limitations [32].
Data transfer relies on local neighborhood awareness, without global topology knowledge. The network is assumed to operate in an infrastructure-less and decentralized manner, meaning no central authority manages routing or node behavior. Sensing Units collaborate to maintain connectivity and route data efficiently through shared communication protocols [33].

2.3 Communication Types in WSN

WSN communication can be categorized into several key types, depending on data flow and purpose:

• Node-to-Node (N2N) Communication:
This involves local wireless communication between neighboring sensing units for routing, data aggregation, or coordination [34].

• Node-to-Sink Communication:
This is the main data delivery mechanism where information is forwarded—often through multiple hops—from sensing units to the sink or BS.

• Sink-to-External Network Communication:
This link connects the WSN to broader systems, such as cloud servers or remote monitoring tools, allowing data storage, visualization, or integration with external applications [6].

• Alert Broadcasting Communication:
In security-critical applications such as replica detection, specific messages (e.g., detection alerts) may be broadcast across multiple sensing units to ensure network-wide awareness and response.

2.4 Characteristics of WSNs

WSNs possess unique characteristics that influence protocol design, especially for security and clone detection:

• Resource Constraints:

Sensing Units are highly limited in power, memory, processing, and transmission range, vitally needing lightweight and energy-aware protocols [36].

• Static Topology:

In the scenario considered here, sensing units remain fixed after deployment, enabling stable neighbor relationships and consistent routing paths—favorable conditions for protocols like RSD.

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• Scalability:
WSNs are often deployed with large number of sensing units, ranging from hundreds to thousands, thus demands protocols that scale efficiently without centralized coordination [13].

• Unattended Deployment:
Sensing Units may be left unattended for long periods, especially in remote or hazardous environments, which increases the risk of physical compromise and makes replication detection tough.

• Decentralization:
The absence of centralized management allows sensing units to operate autonomously. Security protocols must therefore work in a distributed manner to ensure resilience and robustness [38].

• Data-Centric Operation:
Unlike traditional networks, WSNs are primarily designed to sense and report environmental data, meaning that communication is often event-driven and optimized for specific sensing tasks.

3. APPLICATIONS OF WSN

WSNs have very vast applications across very diverse sectors due to their ability to operate in harsh or remote environments, give real time surveillance info, and support intelligent industrial automation. There minimal power consumption, flexibility, and ability to be deployed unattended make them vital in modern infrastructure, environmental research, and defense [39],[40].

3.1 Environmental Monitoring

WSNs is vital in collecting scientific data over time from remote or inaccessible locations, hazardous areas, backing eco-friendly efforts and long-term green goals, helping follow environmental rules and support sustainability [2].

• Ecosystem and Climate Monitoring:
WSNs are extensively used in environmental monitoring, collecting data over long periods from remote or hazardous locations. These networks can track parameters such as temperature, humidity, light intensity, air quality, water levels, and biodiversity, providing invaluable info for scientific studies and conservation efforts [42].

• Chemical Leak Detection:
WSNs deployed in a chemical plant enable the creation of an instantaneous wireless network capable of swiftly identifying and reporting any chemical leaks [43].

• Emergency Repurposing:
Repurposed during emergencies like spread of toxic gases, fire, re tasked to track the origin and spread of these dangers. This adaptive capability further provides safety by guiding efficient evacuation routes.

• Tree-Structured Topologies for Stability:

These systems utilize tree structure topology for data route in which every tree consists of expanded capacity devices which synchronize information flow. However, sensing unit which have extensive descendant connections may encounter heightened data transmission

• Scheduled Low-Rate Transmission:

Data collection usually happens at intervals of 1 to 15 minutes, balancing monitoring needs and energy conservation.

3.2 Agricultural Applications

WSNs significantly improve agricultural productivity by providing related and environmental data for farming decisions [3].

• Soil and Crop Health Monitoring:
WSNs are instrumental in monitoring soil moisture levels, optimizing irrigation practices, and ensuring crop health.

• Energy-Conserving Updates:
The low-frequency reporting required for these parameters makes WSNs efficient, conserving energy and prolonging the network's operational lifespan.

3.3 Healthcare and Medical Systems

In this domain, WSNs enable real-time patient monitoring, continuous observation via sensor cameras, body attached, and body installed or injected sensors and other mediums[45].

• Physiological Parameter Tracking:
These networks facilitate continuous observation and tracking of human physiological health parameters.

• Timely Medical Intervention:
Body installed or injected sensors can provide early detection of health anomalies and provides timely medical interventions.

3.4 Industrial and Infrastructure Systems

WSNs boost automation, safety, and operational efficiency in industrial, urban, and public systems [46].

• Machine and Safety Monitoring:

Inside Industrial systems WSNs provide process automation, alarm systems and safety measures. They are used to monitor machinery health, detect gas or similar leaks, and evaluate overall and section wise industrial system efficiency.

• Smart City Infrastructure:

In society development, WSNs are applied in smart city infrastructure development, traffic management, and public safety systems [47].

• Low Installation Overhead:

Unlike traditional wired systems, WSNs significantly reduce operational costs by eliminating the need for extensive wiring.

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3.5 Military Surveillance and Emergency Operations

WSNs offer persistent, autonomous sensing in defense zones and during emergencies [1].

• Perimeter Surveillance:

In military area, WSNs are applied by various types of surveillance and reporting. Sensing Units can detect motion, vibration, or sound and operate silently in border zones.

• Command Alerts and Deployment:

Real-time alerts send to command centers, enabling rapid tactical decisions and situational awareness. Rapid deployment feature is particularly advantageous in emergency response scenarios or military operations, where rapid network setup is crucial.

3.6 Adaptive and Future-Ready Deployments

WSNs have ability to adapt in dynamic environments and evolve with advancing technologies [7].

• Task Switching During Emergencies:

Consider a scenario where a WSN initially deployed for leak detection in a chemical facility is repurposed during emergencies to track the origin and spread of toxic gases. This adaptive capability underscores the versatility of WSNs in dynamic operational environments.

• Emerging Technologies Integration:

The evolution of WSNs continues with advancements in machine learning, edge computing, and artificial intelligence. This enables autonomous decision-making nearer to the information source, decreasing Response time & enhancing responsiveness [50].

• Global Sustainability Role:

As these networks continue to evolve, they promise to revolutionize industries, enhance quality of life, and contribute to sustainable development goals globally.

4. SECURITY AND PRIVACY ISSUES IN WSN

Wireless Sensor Networks (WSNs) are extensively used in environmental monitoring, industrial automation, medical and healthcare systems, and military surveillance. However, their wireless nature, distributed structure, and operation in harsh or remote environments make them vulnerable to a wide range of security and privacy threats [51]. WSNs are composed of compact sensing units with limited processing power and energy, which makes applying conventional cryptographic protections a significant challenge [52]. Additionally, their often unattended deployment increases the risk of physical tampering, data interception, and replication.

A major threat to WSNs is the node clone attack, where an attacker physically captures a legitimate sensing unit, extracts its credentials or ID, and introduces one or more replicas into the network [53]. These replicated nodes may participate in routing, data aggregation, or monitoring while secretly launching attacks such as data manipulation, false reporting, or network disruption. Other significant attacks include Sybil attacks, where a single sensing unit assumes multiple fake identities to compromise network protocols [54]; sinkhole attacks, where malicious sensing units mislead nearby sensing units to route all data through them [55]; selective forwarding, where sensing units drop selected packets [56]; and denial-of-service (DoS) attacks, which flood nodes or sinks with bogus messages [57]. Unauthorized data access is another key issue, especially in applications that deal with sensitive health, environmental, or industrial information [58]. Additionally, traffic analysis attacks can expose sensing unit positions, detect events, or identify high-value sensing units.

Privacy concerns are equally important in WSNs, particularly in sectors such as healthcare and defense. Unauthorized eavesdropping on data transmission may lead to disclosure of user identity, physical location, or sensor roles [59]. Therefore, maintaining data confidentiality, integrity, location privacy, and anonymity is critical in privacy-sensitive deployments.

To protect WSNs from these threats, multiple lightweight and distributed mechanisms have been proposed. Authentication techniques are used to validate sensing unit identity and prevent unauthorized network access [23]. Symmetric encryption methods, such as those implemented in ZigBee or BLE protocols, offer efficient protection for sensitive data [61]. Pseudonym schemes and location obfuscation techniques are used to ensure anonymity and reduce traceability [62]. Trust-based models continuously evaluate sensing unit behavior and isolate those that act abnormally [63]. Intrusion Detection Systems (IDS) are also implemented in energy-aware forms to detect and respond to attack patterns such as unusual packet drops or false claims [64].

Solution proposed in this research called as Randomized Secure Detection (RSD) protocol and Mechanisms are tailored specifically for node clone attack threat which includes scenarios such as replication of legitimate nodes, false data injection, and routing disruption. RSD mitigates these threats using randomized witness routing, adaptive claim broadcasting, and a secure alert generation (secure alert mechanism) to detect replicas (node clones) without requiring high energy or complex computations [65]. These characteristics make proposed solution suitable for practical deployment in resource-constrained environments.

Despite these defenses, several unresolved issues remain. Ensuring real-time responsiveness, mobility support, and scalability while maintaining low communication overhead, remains a continuing challenge [66]. Moreover, balancing privacy preservation with the ability to trace and respond to attackers (i.e., accountability) remains difficult in WSNs. Additionally, integration with blockchain, edge computing, or IoT infrastructures creates new attack surfaces that require multi-layered, context-aware security frameworks [60].

In summary, WSNs face diverse and evolving security challenges that require energy-efficient, adaptive, and distributed protection strategies. Developing such systems is essential for building secure, reliable, and cost-effective WSNs for long-term operation in mission-critical environments [49].

Given these challenges, the following section details the proposed RSD protocol architecture and its components, designed to detect sensing unit replication attacks effectively in static WSNs.

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5. RSD PROTOCOL: ARCHITECTURE WORKING & ADVANTAGES

5.1 Problem Statement

In Wireless Sensor Networks (WSNs), among the most dangerous and challenging attacks is the node clone or replication attack. In such an attack, a legitimate sensing unit is physically captured by an adversary, its credentials are retrieved, and one or more clones of this sensing unit are introduced into different parts of the WSN. These replicated sensing units appear legitimate to the system and may participate in normal communication, routing, and data aggregation, while secretly performing malicious actions. Given the constrained nature of WSNs—limited energy, memory, processing power, and decentralized design—it becomes necessary to develop lightweight (minimal resource usage), low-power-consuming, and distributed mechanisms for clone detection [9],[13].

5.2 Phases of the RSD Protocol

The proposed Randomized Secure Detection (RSD) protocol operates in four coordinated phases that together enable robust and decentralized clone detection in static WSNs.

5.2.1 Broadcast Phase

Each sensing unit periodically broadcasts a location claim containing its ID, current location, and timestamp. The message is authenticated using lightweight (minimal resource usage) cryptographic hashing techniques to ensure integrity and freshness.

5.2.2 Randomized Routing Phase

Rather than flooding the network, the RSD protocol employs a pseudo-random function to forward each location claim to a limited number of witness nodes. These witness nodes are selected probabilistically based on the ID and timestamp, and the route taken is randomized to prevent attackers from predicting the path.

5.2.3 Clone Detection Phase

When a witness node receives multiple location claims with the same ID but different locations or conflicting timestamps, it detects the presence of a clone. This decentralized comparison mechanism increases robustness and detection probability without depending upon on a central base station (BS).

5.2.4 Alert Propagation Phase

Upon detecting a clone, the witness node generates an alert message, which is transmitted securely to the BS and surrounding sensing units. These alert messages allow the network to isolate, ignore, or remove the cloned sensing unit from routing paths and future data communication.

5.3 Architectural Features

The RSD protocol is designed for a static, homogeneous, and multi-hop WSN architecture. Sensing units are strategically deployed across the defined geographic areas and remain stationary after deployment. Each sensing unit is equipped with limited energy and computation capacity, requiring the protocol to be lightweight and efficient.

The WSN relies on randomized multi-hop communication to forward identity claims toward designated witness nodes, which act as verification points. These witness nodes are randomly selected using a pseudo-random algorithm based on the node's identity and broadcast timestamp, ensuring unpredictability and fairness in detection duties.

The architecture avoids dependency on any central authority or controller. Instead, it leverages distributed decision-making, where sensing units collaborate autonomously for clone detection and alert propagation. The BS serves as a data sink and final alert receiver, but not as an active participant in detection logic.

The architectural design aligns well with the real-world characteristics of WSNs, including decentralized control, event-driven communication, and the need for minimal power consumption.

5.4 Advantages of RSD Protocol

The RSD protocol offers the following benefits in safeguarding WSNs against sensing unit replication attacks:

- Random Witnessing: The use of randomized routing and witness selection ensures unpredictability, making it difficult for adversaries to anticipate detection nodes.
- Energy Efficiency: Unlike protocols that use full flooding or heavy cryptography, RSD minimizes communication overhead and computational load.
- Decentralized Operation: There is no single point of failure. All sensing units do equal participation in detection, increasing robustness and resilience.
- Lightweight Security Integration: Optional support for lightweight cryptographic techniques/functions and compatibility with blockchain extensions (for immutable alert logging) provides enhanced security without overloading sensing units.

These architectural and operational strengths make RSD a suitable and scalable solution for deployment in static WSNs deployed in remote or mission-critical environments.

6. PERFORMANCE ANALYSIS AND COMPARATIVE DISCUSSIONS

To analyze the performance of any proposed solution, it is essential to compare its behavior with existing solutions and mechanisms. This section outlines a performance evaluation of the RSD protocol in comparison with detection mechanisms such as RED (Randomized, Efficient, and Distributed) mechanism, using simulation results based on Network Simulator, as well as performance evaluation and analytical comparisons with SET (Simple Energy-efficient Trust) and Random Key Predistribution techniques [19],[45],[48].

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6.1 Simulation Setup and Parameters

The simulation was conducted using NS 2, modeling(sim.) a static WSN with 100 to 500 nodes arbitrarily deployed in a 1000 m × 1000 m area. The communication model was based on the MAC protocol IEEE 802.15.4, mimicking real-world constraints of limited energy and transmission ranges (in sensor nodes).

Key metrics examined and analyzed:
- Detection Accuracy
- Packet Delivery Ratio (PDR)
- Energy Consumption
- Average Delay
- Communication Overhead

The Key metrics and comparisons are grounded in the thesis, from which 'Table: Detection Rate Comparison under Varying Clone Node Conditions' is presented again here as Table 6.1

Table 6.1: Detection Rate Comparison under Varying Clone Node Conditions.

No. of Cloned Nodes Injected into N/W	Detection Rate (%) using RED Protocol	Detection Rate (%) using RSD Protocol
5	32	62
10	36	70
15	38	74
20	40	80
25	41	83
30	39	82

Table 6.1 shows the detection rate of cloned nodes under growing rising attacks scenarios. Comparing the traditional RED protocol with the proposed RSD protocol, it is recorded that the RSD protocol is consistent in performing superior than RED in detecting clone attacks, especially as the number of malicious nodes grows.

6.2 Results Overview

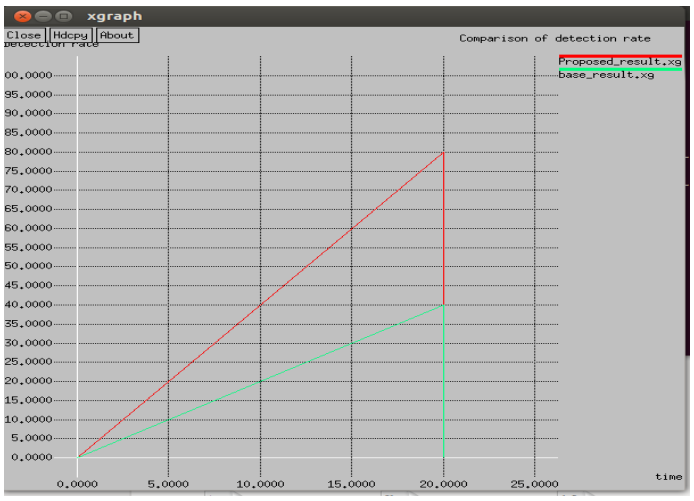

Figure 6.1: Comparison of Detection Rate. This graph shows detection rate of RED vs. RSD with increasing clone count:

- Y-axis: Detection Rate (%)
- X-axis: Number of Clone Nodes
- Two lines: RED protocol (lower green line), RSD protocol (higher red line)

Table 6.1 and Figure 6.1 show that the RSD protocol significantly performs superior than the RED protocol in identifying cloned nodes. The detection rate grows with the number of cloned nodes but remains continually higher under RSD. RSD protocol achieved up to 80–83% detection rate for medium to high clone node injections, whereas the RED protocol saturates around 40–41%, which demonstrates the improved performance of the proposed method.

6.2.1 Comparative Summary with RED Protocol

Table 6.2: Comparative Summary Table (with RED Protocol)

Metric	RED Protocol	RSD Protocol (Proposed)
Packet Delivery Ratio	Lower	Higher
Energy Consumption	Higher	Lower
Detection Accuracy	Medium	High
Communication Overhead	High	Low
Average Delay	Higher	Lower

Key metrics, Graphical analysis (Figure 6.1), Table 6.1 and Table 6.2 show that compared to the RED protocol, the proposed RSD protocol demonstrates advanced performance in several key areas:

- RSD continually performs superior than RED in terms of Packet Delivery Ratio, Average Delay, and Energy Consumption (because RED used up more energy and RSD conserved more energy).
- Detection accuracy is higher in RSD, due to its decentralized witness-based verification.
- Communication overhead is significantly lower in RSD than in flooding-based-strategy like RED. RSD shows reduced communication overhead and fewer detection false positives, ensuring superior energy efficiency and greater detection accuracy under resource-constrained environments.
- The RSD protocol maintains higher packet integrity due to its randomized claim routing and effective detection mechanisms, which prevent cloned sensing units from corrupting or hijacking data paths.

RSD continually performs superior than RED in simulation results conducted on NS-2

6.2.2 Comparative Summary with Other Protocols

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Table 6.3 Comparative Summary Table (with Other Protocols & Mechanisms)

Protocol	Detection Accuracy	Energy.Consumption	Commun-ication Overhead	Scalability
RED	Medium	Medium	High	Moderate
SET	Low	Low	Low	Low
Random Key Pre-distribution	Medium	High	High	Moderate
RSD (Proposed)	High	Low	Low	High

Table 6.3 outlines the performance evaluation and analytical comparisons of RSD with other mechanisms and techniques. As seen in Table 6.3 and stated below, the RSD protocol provides significant improvements when compared with several existing node clone detection techniques:

• Compared to RED: RSD improves energy efficiency by avoiding full-network flooding and adopting lightweight randomized witness selection. It also achieves higher detection accuracy and minimizes false positives through adaptive claim broadcasting.

• Compared to SET (Simple Energy-efficient Trust) protocols: RSD provides superior scalability and lower communication overhead, as SET depends on trust propagation mechanisms that are computationally expensive in large networks

• In contrast with Blockchain-based detection frameworks, RSD avoids the high computational burden and memory demand of distributed ledgers, making it more suitable for resource-constrained sensing units.

• Compared to Mobile Agent-Based protocols: RSD removes the need for mobility infrastructure and agent maintenance, simplifying deployment and enhancing network robustness.

These comparative strengths make RSD a versatile, energy-aware, and practical protocol for real-world WSN deployments, particularly in static, low-power, and unattended environments.

6.3 Interpretation

The RSD protocol out performs traditional clone detection mechanisms such as RED across multiple performance metrics, including detection accuracy, energy consumption, communication overhead, and scalability. It's randomized claim routing, local verification, and low-overhead alert propagation mechanisms minimize energy use and reduce network congestion by avoiding full-network flooding. Additionally, RSD's use of lightweight cryptographic functions and a fully decentralized detection model eliminates reliance on central coordination, making it particularly well-suited for large-scale, resource-constrained, and static WSN deployments.

7. CHALLENGES AND FUTURE DIRECTIONS

Despite the promising results and architectural strengths of RSD and its effectiveness and high efficiency in detecting node replication attacks, it still faces challenges that must be addressed with future enhancements and solutions to ensure its broader adoption and robustness in diverse WSN environments [44].
Also, several open challenges, limitations, and security issues remain with WSNs, which are not directly addressed by RSD, such as Sybil attacks, sinkhole attacks, selective forwarding, or denial-of-service attacks, as RSD is designed to address node clone attacks. These issues require additional mechanisms like behavior monitoring, collaborative filtering, or physical fingerprinting [35],[37],[41].

7.1 How does RSD, through its versatility, help address WSN security issues beyond its scope & how can it be further advanced:

• Sybil Attacks: RSD does not explicitly address Sybil attacks, where a single node assumes multiple fake identities. However, RSD detects replicated IDs with conflicting location / time info, so RSD provides in-direct Sybil resistance if the impersonation resembles cloning [30].
As a future direction, RSD can be combined with trust-based models, identity verification, or Sybil-specific detection layers to enhance security coverage.

• Sinkhole Attacks: In this, a compromised node transmits false routing information to attract all nearby traffic towards itself, creating a "sinkhole" through which the attackers can do — eavesdropping on data, selectively drop or alter packets, and launch subsequent attacks (e.g., false data injection). RSD's use of randomized multiple-hop routing and decentralized witness selection minimizes the likelihood of a single compromised node intercepting clone detection alerts [29].
To actively identify or isolate sinkhole nodes, RSD could be combined with secure routing or trust-based protocols in future developments.

• Selective Forwarding: If a malicious node performing selective forwarding is a clone, RSD will detect and isolate it, thereby mitigating its capability to drop packets. By using multiple witness nodes and randomized routing, RSD minimizes reliance on any single node for message forwarding, limiting the impact of a selectively forwarding node [21].
As future enhancements, RSD could include integrating nearby nodes monitoring, where nodes track packet forwarding behavior, and incorporating trust-based scoring systems to detect and isolate compromised nodes based on observed communication reliability.

• Denial-of-Service attacks: By avoiding centralized processing and using randomized witness selection, RSD minimizes the risk of bottlenecks or single points of failure that are typically targeted in DoS attacks. Additionally, limited broadcasting ranges and energy-aware communication help minimize unnecessary network traffic, in-directly lowering susceptibility to flooding-based DoS scenarios [20].

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As future direction- in RSD introduce rate control at each node to limit the frequency of broadcasting and forwarding actions, preventing attackers from overwhelming the network with excessive claim messages. And integrate simple statistical or rule-based intrusion detection to monitor abnormal traffic patterns (e.g., sudden spike in claim messages, enabling early detection and throttling of potential DoS attempts. These enhancements would strengthen RSD's resilience to flooding-based and resource-depletion DoS attacks without significantly increasing energy consumption.

7.2 Current Limitations of RSD Protocol

Despite its benefits, the RSD protocol faces several challenges that need to be addressed for broader adoption:

• Limitations in Clone Collaboration Scenarios: In scenarios where multiple cloned nodes collaborate, the randomized routing may not be sufficient to ensure detection, especially if witness paths are strategically avoided.

• Dynamic Network Support: RSD is optimized for static WSNs. Its performance in mobile or highly dynamic environments remains uncertain and untested.

• Although RSD is energy-efficient overall, some nodes may still bear more routing or witnessing responsibility, leading to localized energy depletion.

• Scalability under Dense Deployment: The efficiency of randomized witness selection may go down in highly dense WSN deployments. RSD must be optimized to scale in densely deployed WSNs without increasing latency, increasing false positives, and longer detection delays

7.3 Future Enhancements and Research Directions

To overcome these limitations, the following directions are suggested for future development of the RSD protocol. Future enhancements may explore integration with emerging technologies:

• Blockchain Integration: Incorporating a lightweight block chain layer could provide unchangeable logging of detection events, enhancing accountability and preventing tampering with alerts.

• Edge Computing Synergy: Assigning clone detection tasks to edge nodes or microservers could reduce latency and allow real-time decision-making with minimal burden on sensing units. Edge computing is expected to reduce response latency by processing alerts locally, thus enhancing real-time decision-making.

• AI-Driven Behavior Analysis: Machine learning algorithms could be trained to detect abnormal behavior or communication patterns, complementing the rule-based clone detection used in RSD.

• Mobility Supporting Variants: Designing a variant of RSD that supports mobile sensing units will expand its applicability to vehicular or body sensor networks.

• Trust-Based Witness Selection: Integrating a trust score for each node to guide witness selection may enhance detection reliability and reduce vulnerability to compromised witnesses.

• Hybrid Detection Models: Combining deterministic-checks (e.g., localization verification) with RSD's probabilistic routing may improve clone detection in security-critical deployments.

• Fine-tuning claim frequency, witness selection algorithms, and alert propagation strategies can further optimize the RSD protocol for energy consumption, latency, and resilience.

In future research, simulation studies should be extended to include collusion scenarios, dynamic topologies, and multiple-hop witness correlation. Real-world testbed deployment can also validate the feasibility of RSD under practical constraints.

8. CONCLUSION

This research presents the RSD protocol as a practical and efficient solution to the critical challenge of node clone attacks in WSNs. RSD operates in a lightweight, decentralized, and energy-efficient manner, utilizing randomized witness selection, secure claim broadcasting, and alert propagation to detect replicated nodes in static, resource-constrained environments.

Simulation-based evaluation and architectural analysis show that RSD out-performs traditional protocols such as RED and SET in terms of detection accuracy, energy consumption, and scalability. Its design aligns with the real-world characteristics of WSNs — minimal resources, lack of centralized control, and the need for robustness in mission-critical deployments like environmental monitoring, defense systems, and industrial automation.

While RSD effectively addresses clone detection, challenges such as mobility support, collusion resistance, and broader attack resilience remain open. Future work will focus on enhancing RSD through blockchain-based alert logging, edge computing for low-latency response, and AI-driven behavior analysis to improve its applicability in dynamic and diverse WSN environments.

The proposed protocol represents a promising advancement towards building secure, scalable, and adaptive WSNs capable of withstanding evolving security threats in critical applications.

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