RFIDNet: A Protocol for Effective Multiple RFID Readers Collaboration

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***Abstract*—Dense RFID environments pose significant challenges, such as reader collisions, tag interference, and scalability issues, which degrade system performance and reliability. This paper introduces RFIDNet, a novel protocol designed to address these challenges by dynamically coordinating reader activities and optimizing network resource utilization. The proposed RFIDNet is an innovative framework of advanced mechanisms that include a Carrier Sense Multiple Access with Reader Arbitration (CSMARA) scheme for efficient reader coordination, Dynamic Frequency Hopping (DFH) for interference mitigation, and merging Frequency and Time Division Multiple Access (F/TDMA) with Reduce Coverage Control (RCC) to handle unresolved contention. Experimental validations using a Universal Software Radio Peripheral (USRP) testbed and MATLAB simulations demonstrate that RFIDNet improves the overall system performance compared to the baseline. This confirms RFIDNet's robustness and scalability, making it a viable solution for real-world, dense RFID deployments.**

***Index Terms*—Dense RFID environment, Scalability, Carrier Sense Multiple Access with Reader Arbitration (CSMARA), Frequency Time Division Multiple Access (F/TDMA), Reduce Coverage Control (RCC), Dynamic Frequency Hopping (DFH).**

I. Introduction

The Radio Frequency Identification (RFID) technology has established itself as a critical enabler of automation in various industries, including supply chain management, logistics, retail, and healthcare [1]–[3]. It allows for seamless tracking and management of assets, significantly reducing the need for manual intervention and improving operational efficiency. However, as RFID deployments scale, particularly, in dense environments where a large number of readers and tags operate simultaneously in close proximity—such as large warehouses, distribution centers, and retail spaces—several significant challenges arise that affect such systems' effectiveness and reliability [4]–[7].

In dense RFID environments, managing reader-to-reader (RR) collisions is a major challenge. When multiple readers simultaneously interrogate overlapping sets of tags, signal interference and corrupted responses lead to reduced system throughput. Redundant tag reads (i.e., when multiple readers interrogate the same tag) further exacerbate the network load and complicate data aggregation, potentially, causing inconsistencies in inventory records [8]. Traditional protocols such as Carrier Sense Multiple Access (CSMA) as deployed in prior works [9], [10], rely on random backoff mechanisms to mitigate collisions but struggle in dense conditions, resulting in a high probability of simultaneous transmissions, especially when readers are closely positioned and communication channels are limited [11].

Scalability is another concern. As the number of readers and tags increases, the complexity of managing communications grows exponentially, creating bottlenecks and limiting the ability to maintain high performance. Existing RFID protocols and RFID middleware solutions [12] often rely on static, simplistic mechanisms for reader coordination, which are not sufficiently adaptive to the dynamic conditions of dense environments. These limitations lead to frequent signal interference, missed readings, inefficient data aggregation, and performance degradation.

To address these issues, authors in [9] proposed a receiver-based CSMA that improves collision avoidance through carrier sensing but may struggle in dense environments with overlapping reader zones and high tag densities. A-RFID [10], which mimics CSMA, adjusts back-off intervals for specific applications but doesn't fully address the complexities of dense passive RFID environments. Protocols like PULSE [13] introduce significant overhead and latency due to periodic beacon transmissions, impacting energy efficiency. Fixed window sizes in protocols like DCS [14] or rigid backoff schemes result in performance issues in varying network densities. TMIA [15] effectively handles tag collisions but lacks efficient strategies for managing reader collisions, which are crucial in dense RFID environments, and may suffer high latency.

In this paper, we introduce RFIDNet, a multi-layered protocol specifically designed for dense RFID environments. RFIDNet enables effective collaboration and coordination among multiple RFID readers by introducing advanced collision management mechanisms and scalability. At the heart of RFIDNet is the Carrier Sense Multiple Access with Reader Arbitration (CSMARA) protocol, which extends the traditional CSMA by incorporating a dynamic and intelligent arbitration mechanism. This protocol allows readers to coordinate their transmissions through real-time communication to exchange information about their intended transmissions. By considering factors such as reader-to-tag distance, received signal strength, and historical transmission patterns, CSMARA significantly reduces the likelihood of collisions, thereby improving the system throughput. RFIDNet employs fallback mechanisms to

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ensure continuous system reliability and a probabilistic model for frequency hopping. Fig. 1 illustrates the RFIDNet system's functions of each protocol layer.

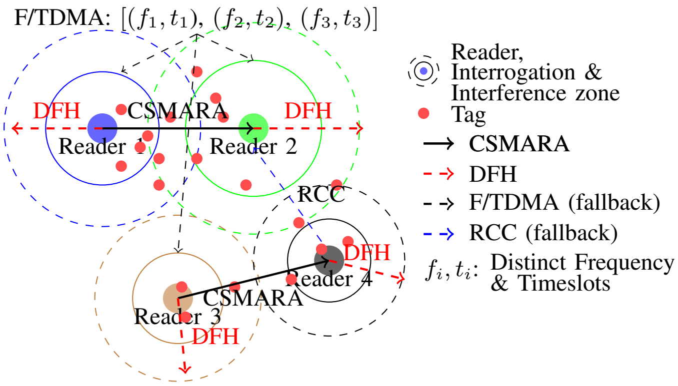

Fig. 1: The diagram illustrates the RFIDNet system's functions: **CSMARA** manages reader priority and resolves conflicts between readers (1, 2) and (3, 4). If arbitration fails or under challenging conditions, RFIDNet falls back to Frequency and Time Division Multiple Access (**F/TDMA**) as in the scenario of readers 1, 2, and 3. The protocol dynamically adjusts the readers' coverage through Reduce Coverage Control (**RCC**) to maintain performance thresholds for readers 2 and 4. RFIDNet uses Dynamic Frequency Hopping (**DFH**) to reduce frequency conflicts during tag interrogation.

RFIDNet is designed for scalability, incorporating efficient data aggregation to reduce redundant tag reads and optimize network resource use. To this end, most works on RFID collision resolution protocols rely on simulations with idealized models. We prototype and evaluate RFIDNet using Universal Software Radio Peripheral (USRP) hardware, demonstrating significant improvements in collision reduction, scalability, and overall system performance, making RFIDNet a robust solution for real-world RFID systems in dense environments. We summarize this paper's main contributions as follows:

- Antenna-level Collision Management: RFIDNet reduces reader collisions based on antenna placement to improve system throughput, reduce latency, and eliminate the risk of having redundant readers.
- Decentralized Multiple Reader Coordination: We introduce a 5-layer RFID protocol stack with the proposed RFIDNet layer (Fig. 2), which decentralizes reader communication, allows readers to manage operations autonomously, and reduces collisions and interference in dense environments.
- Scalability and Efficient Data Aggregation: RFIDNet is designed to scale efficiently in dense environments, incorporating data aggregation techniques that minimize redundant tag reads and optimize network resource utilization as confirmed by our MATLAB simulations.
- We also prototype and evaluate the RFIDNet protocol with USRP, demonstrating its practical applicability and effectiveness in reducing collisions and improving system performance in real-world RFID deployments.

The rest of this paper is organized as follows: Section II presents the problem statement and preliminaries. Section III describes the proposed methods—design and functionalities of the RFIDNet protocol. Section IV covers the experimental study and discussions. Section V concludes the paper.

II. Problem Definition and Preliminaries

A. Problem Statement

In dense RFID systems, where multiple readers $\mathcal{R} = \{R_1, R_2, \ldots, R_M\}$ and tags $\mathcal{T} = \{T_1, T_2, \ldots, T_N\}$ operate simultaneously, overlapping interrogation zones introduce significant performance challenges. These challenges include reader-to-reader (RR) and tag-to-tag (TT) collisions, which degrade throughput and system efficiency. Reader-to-tag (RT) collision resolution is a given to RFIDNet's operation, thus, we focus on RR and TT collision resolution in this paper.

Reader-to-reader (RR) collisions occur when multiple readers attempt to interrogate overlapping sets of tags simultaneously, causing interference. The collision probability $P_{RR}(i,j)$ between readers R_i and R_j can be expressed as:

$$P_{RR}(i,j) = 1 - e^{-\lambda_{ij} T}, \tag{1}$$

where λ_{ij} is the rate of simultaneous transmissions between overlapping readers R_i and R_j, and T is the interrogation time. The total collision probability P_{RR_total} across M readers is the sum of individual collision probabilities:

$$P_{RR\_total} = \frac{2}{M(M-1)} \sum_{i=1}^{M} \sum_{j=i+1}^{M} P_{RR}(i,j). \tag{2}$$

Tag-to-tag (TT) collisions occur when multiple tags respond simultaneously to a reader within a shared interrogation zone, resulting in data corruption. The collision probability for k tags responding to a single reader P_{TT} is modeled as:

$$P_{TT}(t) = 1 - \prod_{i=1}^{k} (1 - p_i(t)), \tag{3}$$

where $p_i(t)$ represents the time-varying probability of tag i's response within the reader's time slot, dependent on interference conditions or mobility and k is the number of tags responding within the interrogation zone (s.t. $2 \leq k \leq N$, which rules out the probability of only one tag responding). As the number of readers M and tags N in the system increases, the likelihood of collisions rises exponentially, impacting throughput and latency. The system's throughput T_{sys} can be expressed as a function of collision probability:

$$T_{sys} = T_{max} \times \left[(1 - P_{RR\_total}) \cdot (1 - P_{TT})\right], \tag{4}$$

where T_{max} is the maximum achievable throughput in a collision-free scenario. The system scales poorly if collision probabilities are not minimized, resulting in diminished throughput as N and M grow. Traditional RFID systems struggle with this scalability problem, lacking mechanisms for coordinating multiple readers and managing interference. Without a coordination protocol, the system performance degrades, leading to inefficiencies and high collision rates.

B. RFIDNet Preliminaries

Fig. 2 illustrates our proposed RFID protocol stack, emphasizing how RFIDNet operates as a layer between the Data Link Layer and Transport Layer, while leveraging the underlying capabilities of the EPCglobal Class 1 Gen 2 standard at the data link layer. Such separation of functionalities allows RFIDNet to manage reader coordination and collision avoidance without modifying the established tag interrogation processes defined by the Gen 2 standard, thus maintaining backward compatibility.

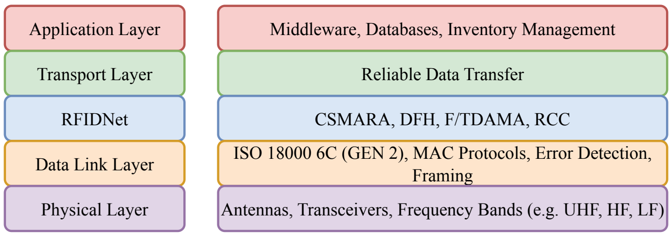

Fig. 2: Proposed RFID Protocol Stack with RFIDNet. Our DFH, F/TDMA, and RCC leverage RFIDNet layer information to control the reader's physical and data link layers parameters to improve system efficiency.

At the *Physical Layer*, RFIDNet utilizes the existing RF signal transmission and reception mechanisms provided by Gen 2 compliant readers and tags, ensuring that it operates within the regulatory constraints and frequency bands established for RFID communication. The Gen 2 protocol, operating at the *Data Link Layer*, handles the core tag interrogation functionalities, including inventorying, reading, and writing tags, and ensures data integrity and collision management at the tag level through anti-collision algorithms and error correction techniques. The innovation of *RFIDNet* lies in the our proposed layer, where it introduces advanced coordination mechanisms, including CSMARA, DFH, F/TDMA, and RCC. These mechanisms work synergically to enhance reader-to-reader communication and coordination, effectively reducing collisions and redundant reads, which are common challenges in dense RFID environments. For instance, if CSMARA struggles with high reader density, the protocol shifts to F/TDMA or RCC, while DFH optimizes frequency selection. The *Transport Layer* is responsible for connection management, flow control, and error correction, ensuring reliable data transfer and maintaining communication sessions between readers and enterprise applications. Lastly, the *Application Layer* comprises application protocols and APIs that integrate RFID data with enterprise systems, providing user-friendly interfaces, and supporting diverse application requirements. This layered structure allows RFIDNet to seamlessly integrate with existing RFID systems, enhancing performance and scalability without necessitating modifications to the current infrastructure.

III. Proposed RFIDNet

A. RRFIDNet Overview

RFIDNet uses a specialized packet-based communication system for inter-reader coordination in dense RFID environments, focusing on avoiding collisions and optimizing tag interrogation. Readers proactively send request messages to neighboring readers before interrogating tags, ensuring only authorized readers communicate within overlapping zones. To maintain synchronization and share operational status, readers periodically send Alive messages and My Neighborhood Information messages, which inform neighboring readers about operational states, frequencies, and time slots. This enables dynamic adjustments in coverage areas and frequency allocation using protocols like DFH and F/TDMA. RFIDNet also uses Reader Data and RCC messages to adjust coverage and optimize performance. The system operates in the 900 MHz to 930 MHz spectrum (supporting possible reconfiguration and parameterization for other regional frequencies), with specific frequency allocations for different functions: 900 MHz for network discovery and secure key exchange, 901 MHz for reader performance metrics (related to RCC), 929 MHz for response, Alive, and My Neighborhood Information messages, and 930 MHz for request messages. The 902 MHz to 928 MHz band is reserved for reader-tag communication per Federal Communications Commission (FCC) regulations for RFID communications. Robust encoding and queuing mechanisms ensure clear differentiation between message types across these frequencies.

B. Operational Process and Dynamic Adjustment

The RFIDNet multi-reader coordination process to optimize tag interrogation while minimizing collisions in dense RFID environments begins with each reader R_j discovering neighboring readers and updating its network tables. Readers also exchange periodic neighborhood information and "alive" messages. Fig. 3 illustrates the process that a reader R_j interrogates a tag T_i. It broadcasts a "Request to Read" (RTR) and initializes its priority arbitration score $\Phi(R_j) = 0$. Arbitration among readers is managed by CSMARA, where each reader computes a score using (5) to determine access to T_i. The arbitration decision $A(R_j, R_k, T_i)$ based on (6) grants permission to the reader with the highest score, while others back off and decrement the Time to Live (TTL) counters for their RTR packects. If successful, the reader proceeds with tag interrogation using DFH (see (10) and (11)) to avoid frequency conflicts. If no reader wins and the TTL expires, the system falls back to F/TDMA, which ensures that readers start hopping from distinct frequency-time slots, such that $\forall R_j, R_k \in \mathcal{R},\ j \neq k : (f_j \neq f_k) \wedge (t_j \neq t_k)$. This guarantees that readers use different frequencies f_j and time slots t_j to avoid collision. If a reader's reading rate falls below a predefined threshold, the algorithm invokes RCC, adjusting the reader's power P_j to optimize coverage with (12) and (14). Upon completion, the reader broadcasts a "DONE" message and returns to idle mode. The combined use of CSMARA, DFH, F/TDMA, and RCC ensures efficient reader coordination, reducing collisions and improving overall system performance in dense RFID environments.

The execution of RFIDNet is determined by the level at which the network and antenna tables, as well as the neighborhood register, are updated—whether at the antenna level or the reader level. This comprehensive approach enables RFIDNet to support up to 255 concurrent readers per network, providing a scalable and reliable solution for modern RFID systems. It is worth noting that the RFIDNet sub-protocols discussed below can be executed standalone in the RFID framework.

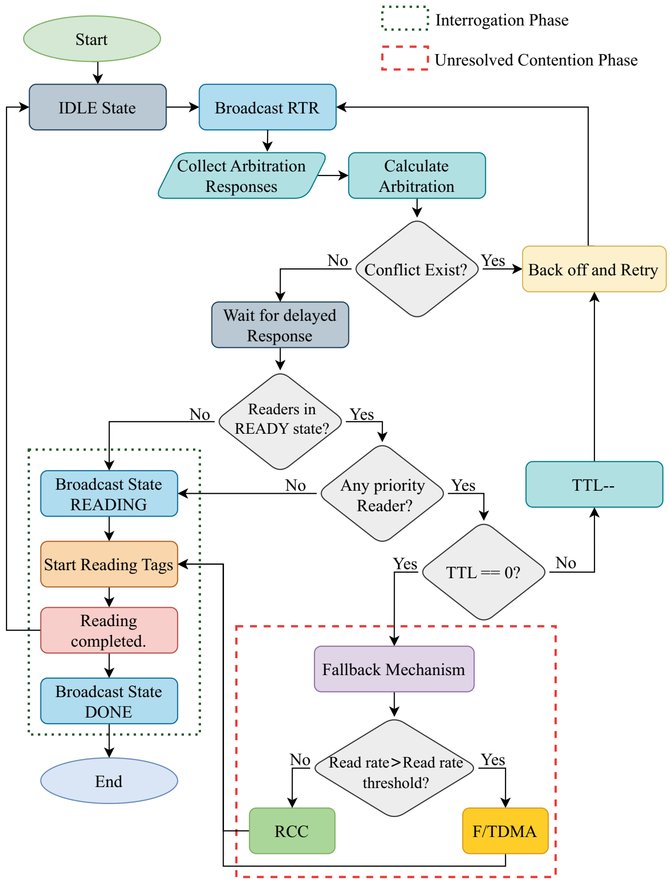

Fig. 3: An illustration of the RFIDNet reader coordination and tag interrogation process.

1) Carrier Sense Multiple Access with Reader Arbitration (CSMARA): After broadcasting its request, the requesting reader R_j receives responses from the nearby readers R_k. Each response includes the relevant information, such as priority, historical success rate, and current state of the responding reader. The requesting reader then computes an arbitration score based on the received responses as follows:

$$\Phi(R_j, R_k, T_i) = P(R_j) + \gamma \cdot h(R_k) + \delta \cdot I(S(R_k) = \text{ready}), \tag{5}$$

where $P(R_j)$ is the priority of the requesting reader in [0,1]; $h(R_k)$ the historical success rate of the responding reader R_k which is a counter obtained from the response message; $S(R_k)$ is the current state of the responding reader R_k; $I(S(R_k) = \text{ready})$ is the indicator function that is 1 if R_k is ready, and 0 otherwise; γ and δ are weight parameters. Reader R_j makes its arbitration decision based on the responding readers' responses by computing

$$A(R_j, R_k, T_i) = \begin{cases} 1, & \text{if } \Phi(R_j, T_i) \geq \Phi(R_k, T_i), \forall R_k \\ 0, & \text{if } \Phi(R_j, T_i) < \Phi(R_k, T_i), \exists R_k. \end{cases} \tag{6}$$

The adaptive process involves dynamically adjusting the arbitration strategy based on the outcome of previous arbitration decisions. The weights γ and δ in the arbitration score are updated as follows with empirically tuned update rate α:

$$\gamma_{new} = \gamma_{old} + \alpha \cdot (\text{Success Rate} - h(R_j)) \tag{7}$$

$$\delta_{new} = \delta_{old} + \alpha \cdot (\text{State Adjustment Factor}). \tag{8}$$

The efficiency E_{CSMARA} of arbitration is evaluated as

$$E_{CSMARA} = 1 - \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{M-1} \sum_{k=j+1}^{M} P_{\text{collision}}(R_j, R_k, T_i), \tag{9}$$

where N is the total number of tags in the network summed over the pairwise collision probabilities of the readers.

2) Dynamic Frequency Hopping (DFH): While COTS readers' hopping sequence is fixed, the proposed DFH dynamically adjusts the operating frequency of readers to minimize both RR and TT collisions by avoiding congested channels during the inventory cycle. The selection of a next hop frequency f_k from a set $\mathcal{F} = \{f_1, f_2, ..., f_K\}$ is based on a weighted cost function:

$$f_k^* = \arg\min_{f_k \in \mathcal{F}} \left\{ \lambda_1 I(f_k) + \lambda_2 \sum_{j \in \mathcal{R}} P_{\text{col}}(R_j \mid f_k) \right\}, \tag{10}$$

where $I(f_k)$ is the measured interference level on frequency f_k, $P_{\text{col}}(R_j \mid f_k)$ is the probability of a collision on frequency f_k for reader R_j, and λ_1 and λ_2 are tunable parameters to balance interference and collision avoidance. The probability $P(f_k)$ of selecting a frequency f_k is given by:

$$P(f_k) = \frac{\exp\left\{-\beta\left(\lambda_1 I(f_k) + \lambda_2 \sum_{j \in \mathcal{R}} P(R_j \mid f_k)\right)\right\}}{\sum_{f_l \in \mathcal{F}} \exp\left\{-\beta\left(\lambda_1 I(f_l) + \lambda_2 \sum_{j \in \mathcal{R}} P(R_j \mid f_l)\right)\right\}}, \tag{11}$$

where β controls the exploration-exploitation trade-off.

3) Frequency and Time Division Multiple Access (F/TDMA): F/TDMA is a fallback mechanism of RFIDNet to ensure reliable operation when dynamic arbitration and frequency hopping are less effective. The allocation of time slots t_j is governed by $t_j = \lfloor j/Z \rfloor \mod T$, where Z is the total number of time slots, T is the duration of the time frame, $\lfloor \cdot \rfloor$ denotes the floor function, and $\mod$ is the Modulo operation. The assignment of frequencies f_j is cyclic $f_j = f(j \mod K)$, where K is the number of available frequency bands. This ensures each reader operates on a different frequency during its allocated time slot, thus minimizing the collision risk.

4) Reduce Coverage Control (RCC): RCC is another fallback mechanism in the RFIDNet framework that dynamically adjusts the interrogation range of each reader to minimize overlapping coverage area, thereby reducing redundant reads. The transmission power P_j of reader R_j is adjusted based on the tag density $\rho(T_j)$ and the proximity of other readers R_i in the vicinity, as

$$P_j = \min\left\{ P_{\max}, \frac{k_{tp}}{\rho(T_j)} \sum_{i \neq j} \frac{1}{\text{distance}(R_j, R_i)^2} \right\}, \tag{12}$$

where k_{tp} is an empirical transmission power scaling factor.

The objective function to minimize reader-to-reader collision and the overall redundancy in tag reads across the multi-reader network, is given by:

$$\min_{P_j} \sum_{i=1}^{M} \sum_{k=1}^{N} \left(\frac{|R_j(T_k)| - 1}{|R_j(T_k)|} \right), \text{ s.t.: } P_{\text{min}} \leq P_j \leq P_{\text{max}}, \quad (13)$$

where P_{min} and P_{max} are the minimum and maximum allowed transmit power levels, respectively, and $R_j(T_k)$ denotes the set of readers covering tag T_k. The following iterative process determines the optimal coverage area:

$$P_j^{(n+1)} = P_j^{(n)} - \alpha \left(\frac{\partial \mathcal{L}}{\partial P_j^{(n)}} \right), \quad (14)$$

where $\mathcal{L}$ is the function incorporating the redundancy and power constraints, and α is the reduction rate, typically, 0.1.

C. Efficient Data Aggregation Mechanism

RFIDNet mechanisms enable efficient data aggregation across the network, minimizing redundant tag reads and improving scalability. Let $T(R_j)$ denote the tags covered by reader R_j. The total system-wide redundant reads R_{red} are minimized as follows:

$$R_{\text{red}} = \sum_{j=1}^{M} \left(|T(R_j)| - \sum_{k \in R(j)} |T(R_j) \cap T(R_k)| \right), \quad (15)$$

where $R(j)$ is the set of readers within the range of reader R_j. RFIDNet optimizes the network's scalability by minimizing the data transmitted while ensuring all tags are identified by,

$$\min \sum_{j=1}^{M} (D_j - R_{\text{red},j}), \text{ s.t.: } D_j \geq D_{\text{min}}, \quad (16)$$

where D_j is the data load, $R_{\text{red},j}$ is the redundant data for R_j, and D_{min} is the minimum data needed for accurate tag identification.

IV. Experimental Study and Discussions

A. Testbed Setup and Configuration

The experimental validation of the RFIDNet protocol utilized a high-precision testbed featuring clusters of USRP N210 software-defined radios (SDRs) equipped with WBX or SBX daughterboards, configured for both UHF RFID tag communications (902-928 MHz) and RFIDNet control packet transmissions on adjacent frequencies (900 MHz, 901 MHz, 929 MHz, and 930 MHz). An OctoClock-G CDA-2990 provides a stable 10 MHz reference clock and a Pulse Per Second (PPS) signal for each USRP across all reader nodes, ensuring phase-coherent operation essential for the CSMARA mechanism to effectively coordinate transmissions and prevent collisions. A Cisco Catalyst 2960G gigabit Ethernet switch enabled high-speed, low-latency data transfer between the USRPs and a high-performance computer running a customized GNU Radio Companion framework. This framework handles signal processing, protocol management, and collision detection, while custom Python scripts automate operations such as reader arbitration, dynamic frequency hopping, and real-time data logging, supporting comprehensive performance evaluation of RFIDNet in dense RFID environments.

B. Experimental Design

Passive RFID tags ranging from 10 to 100 are deployed in various configurations, with readers placed 2 to 4 meters apart, simulating different levels of tag density from low-density to high-density RFID environments. The experimental setup, designed to reflect real-world challenges such as those faced in warehouse management systems, maintains stability with minimal external radio interference. Transmit power levels are adjusted between 20 to 30 dBm based on the configuration. These settings allow for a thorough evaluation of RFIDNet's scalability and reader coordination efficiency under controlled conditions. Performance metrics such as collision rate, system throughput, latency, and redundant reads are measured across multiple scenarios to assess the protocol's efficiency in managing reader collisions and optimizing system performance. RFIDNet's dynamic adaptability to changing network conditions, efficient resource allocation, and ability to maintain high throughput are systematically tested, providing a comprehensive assessment of its capabilities and its potential to manage dense RFID deployments in real-world scenarios.

C. Experimental Results and Discussions

The experimental evaluation compared the performance of the RFIDNet protocol, implemented on top of the EPCglobal Class 1 Gen 2 standard, to the baseline scenario where the Gen 2 protocol operated independently on the same USRP devices. This approach allowed RFIDNet to leverage the underlying Gen 2 functionalities while introducing additional coordination and dynamic frequency management capabilities. The comparison results are summarized in Table I. Fig. 4 compares the improvements offered by antenna-level collision management (i.e., when internal registers are updated) over reader-level cases in RFIDNet (when registers are empty).

TABLE I: Comparison of Mean Performance Metrics Between RFIDNet and Baseline Protocol in Testbed (USRP) Experiments.

USRP System	Throughput (reads/s)	Latency (s)	Collision Events (counts)	Redundant Reads (counts)
RFIDNet	95.19	151.50	10.40	11.40
Baseline	74.91	319.73	54.80	27.20

RFIDNet significantly enhances the performance of dense RFID systems. Compared to a system without RFIDNet on USRP, our method results in (i) Higher Throughput: Tag detection rate is increased from 74.91 reads/s to 95.19 reads/s, demonstrating that RFIDNet enhances system efficiency by reducing interference and enabling more frequent successful reads. (ii) Lower Latency: Due to the lack of hardware acceleration and optimization that are available in commercial readers, the URSP reader has a significantly low read rate. However, the average latency is decreased from 319.73 s to 151.50 s, indicating that RFIDNet provides faster and more responsive tag reads by reducing delays associated with repeated read attempts. (iii) Fewer Collision Events: Collisions drop from 54.80 to 10.40 with RFIDNet, as readers dynamically coordinate to avoid interference, ensuring smoother operation in dense environments. (iv) Reduced Redundant Reads: The number of unnecessary reads is decreased from 27.20 to 11.40, reflecting more efficient use of system resources as readers minimize duplicate tag reads. Additionally, RFIDNet demonstrates that when a reader is aware of its neighbors through an update of the internal registers, the number of collision events is reduced. Thus, RFIDNet reduces collision resolution to an antenna placement problem (i.e., RF planning).

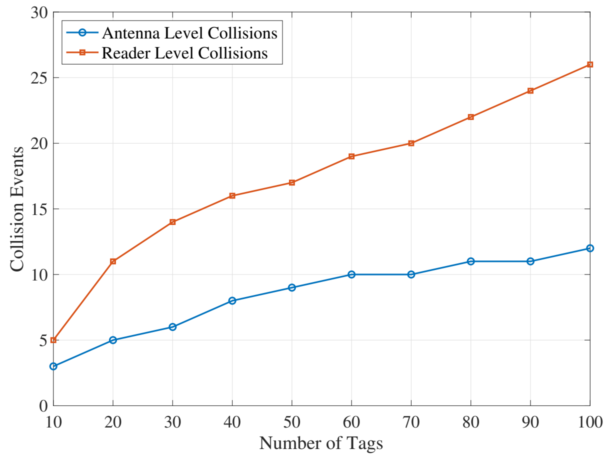

Fig. 4: A comparison of Antenna vs Reader level collision events in RFIDNet.

D. Large-scale Simulation Results and Discussion

To further validate RFIDNet's performance, we conducted simulations using MATLAB to evaluate the protocol under different tag densities (up to 1,000,000 tags), reader configurations (up to 10,000 readers) uniformly distributed across a 500m $\times$ 500m area, and varying network topology (with reader and tag mobility). Readers operated with configurable transmit power between 20 dBm and 30 dBm, within the 902–928 MHz frequency band as per FCC regulations, with distinct sub-bands for inter-reader coordination. These simulations complement the testbed experiments by allowing us to explore larger and denser scenarios that would be impractical in a physical testbed. Each experiment runs for 1,000 cycles and we focus on key performance metrics summarized in Table II to assess the scalability and efficiency of RFIDNet. The simulation results confirm that RFIDNet not only excels in experimental settings but also scales effectively to larger networks with higher tag densities and reader populations making it a viable solution for large-scale deployments.

V. Conclusions

This paper proposed RFIDNet, a comprehensive protocol to tackle the inherent challenges of dense RFID environments, focusing on improving collision management and scalability. By integrating CSMARA (real-time coordination), DFH (frequency optimization), and fallback mechanisms (via F/TDMA and RCC), RFIDNet effectively reduces reader-to-reader and tag-to-tag collisions and optimizes reader coverage to minimize redundant reads. Test experiments showed significant improvements, including an 80% reduction in collisions, 25% increase in throughput, and 60% reduction in redundant reads compared to the baseline. MATLAB simulations also confirmed appreciable improvements by RFIDNet. RFIDNet's compatibility with the Gen 2 standard makes it a practical solution for various industries, offering a scalable and robust framework for next-generation RFID systems.

TABLE II: Performance Comparison of RFIDNet and Baseline Protocols Across Key Metrics from MATLAB Simulations.

Metric (Average)	RFIDNet	Baseline
Total Throughput (reads/sec)	6.525×10^7	5.6524×10^7
Redundant reads (Count)	902	7432
Collisions (Count)	530	8018
Latency (time step)	1×10^4	4.07×10^6
Frequency Utilization Efficiency (%)	98.07%	90.01%
Time Slot Utilization Efficiency (%)	97.53%	91.21%
Energy per Read (J)	3.2×10^{-3}	6.49×10^{-3}
Average Tag Read Rate (tags/sec)	652.5	565.24
Scalability (throughput/reader)	6525	5652.4
Interference Management Efficiency	97.5%	12.21%

Acknowledgment: This work is supported in part by the NSF under Grants CCSS-2245607 and CCSS-2245608.

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