Decentralized Neighborhood Discovery and Management in Dense RFID Systems

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***Abstract*—In dense RFID systems, efficient coordination of multiple readers is crucial to prevent reader-to-reader interference (RRI) and ensure optimal system performance. As the number of readers and tags increases, static frequency and time-slot assignment become insufficient to handle dynamic network conditions, leading to collisions, missed tag reads, and degraded throughput. In this paper, we propose a decentralized neighborhood discovery and management scheme for RFID systems operating in high-density environments. Our approach minimizes interference and improves tag read accuracy by dynamically adjusting communication parameters like frequency and time slots based on current system conditions, which are updated by periodic information exchanges among readers. Experimental results demonstrate that the proposed method significantly improves system scalability, throughput, and reliability. The proposed framework offers a scalable and adaptive solution for dense reader environments.**

***Index Terms*—RFID, Reader-to-Reader Interference (RRI), Dense RFID Systems, Neighborhood Discovery.**

I. Introduction

In dense RFID systems, the overall system performance is exacerbated by *Reader-to-Reader Interference (RRI)* and overlapping interrogation zones, which lead to increased collision rates, missed tag reads, and inefficient resource utilization. For the concurrent operation of multiple readers, neighborhood discovery becomes critical to achieving efficient coordination of the readers to minimize RRI [1]–[3].

Neighborhood discovery as applied to RFID systems refers to the process by which readers identify and maintain communication with other readers within their communication range [3]–[5]. This process is essential for dynamically adjusting communication parameters—frequency, time slots, and coverage or power—based on real-time system conditions to minimize interference. In addition, neighborhood management requires continuous monitoring and updating neighboring readers' states to ensure that the system remains responsive to changes in reader locations, operational states, or configurations. Traditional RFID systems, however, are often inadequate in such dense environments due to their reliance on fixed frequency assignments and time-slot allocations [6]–[9]. Such static approaches fail to account for dynamic changes in the system, such as varying reader densities and interference levels. Consequently, these systems struggle to scale effectively and to maintain high throughput and accuracy as the number of readers and tags increase [10].

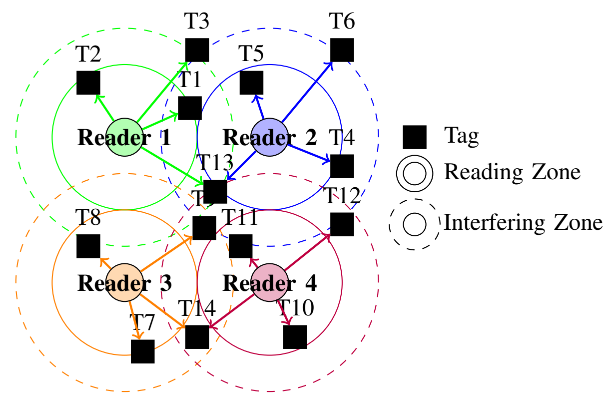

Fig. 1. An illustration of an RFID dense deployment

To address these challenges, we propose a decentralized approach to neighborhood discovery and management for high-density RFID deployments, which allows each RFID reader to autonomously discover its neighbors, exchange operational parameters, and dynamically adjust its communication resources based on real-time environmental conditions. Our method dynamically adjusts communication parameters such as frequency, time slots, and coverage areas by leveraging real-time updates from periodic information exchanges among readers to enhance tag read reliability in environments with dense reader and tag populations. Through experimentation with Universal Software Radio Peripheral (USRP), a software defined radio (SDR) programmable hardware platform, we demonstrate the efficacy of our approach in improving system scalability and performance.

The rest of this paper is structure as follows. We provide the problem statement in Section II and describe the proposed approach in Section III. Section IV present our experimental study and Section V concludes this paper.

II. Problem Definition and Preliminaries

Dense RFID systems are characterized by multiple readers operating in proximity, as illustrated in Fig. 1. The primary challenge in such systems lies in mitigating RRI [11], [12]. This interference is caused by overlapping interrogation zones and leads to collisions, reduced tag read rates, and inefficient resource utilization. Despite the dense mode having been implemented in existing COTS readers, it could not resolve the issue completely [13]. To mitigate these effects, the objective

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of our *neighborhood discovery and management* scheme is to optimize the spatial and temporal distribution of RFID readers.

A. Problem Statement

Consider an RFID system of N readers, each reader i operating within its coverage zone R_i, $i \in \{1, 2, ..., N\}$. The *interference range* of each reader, denoted IR_i, is the area where reader R_i's communication can be detected by a neighboring reader. To minimize the interference while maximizing the tag read throughput, we define the *collision probability* for a reader R_i and its neighbors $R_j \in N(R_i)$ as:

$$P_{\text{coll}}(R_i, t) = 1 - \prod_{j \in N(R_i)} \left(1 - P_{\text{tran}}(R_j, t) \cdot I(f_i, f_j, t)\right), \quad (1)$$

where $N(R_i)$ represents the set of neighboring readers of R_i, and $P_{\text{tran}}(R_j)$ is the probability that neighboring reader R_j is actively transmitting, and $I(f_i, f_j, t)$ indicates if R_j interferes with R_i at time t. Our objective is to minimize $P_{\text{coll}}(R_i)$ for each reader by adjusting the operational parameters such as frequency and time slot allocation.

B. Major Challenges in Dense RFID Systems

1) RRI: For each reader R_i, interference occurs when any of its neighboring reader $R_j \in N(R_i)$ transmits within the interference range IR_i. It is influenced by the transmit power, frequency, and the distance between the readers, following

$$I(f_i, f_j, t) = T_j \cdot d(R_i, R_j)^{-2} \cdot \alpha(f_i, f_j, t), \quad (2)$$

where $d(R_i, R_j)$ is the Euclidean distance between readers, T_j is the transmission power of R_j, and $\alpha(f_i, f_j, t)$ represents a partial interference factor that ranges between 0 and 1 depending on how much the two frequencies overlap.

2) Overlapping Interrogation Zones: Each reader's interrogation zone R_i may overlap with one or more neighboring zones of reader $R_j \in N(R_i)$, leading to collisions. We denote the *normalized overlap* by $A_{\text{overlap}}(R_i, R_j)$, which is the overlapped area over the coverage area. Then, we model the combined interference for R_i from all R_j's as (for simplicity):

$$I_{\text{total}}(R_i, t) = \frac{1}{|N(R_i)|} \sum_{j \in N(R_i)} I(f_i, f_j, t) \cdot A_{\text{overlap}}(R_i, R_j), \quad (3)$$

where $|N(R_i)|$ is the number of neighboring readers overlapping with R_i

3) Dynamic Environmental Conditions: The environment is constantly changing, with variations in reader density, operational state S_i, and transmission behavior $P_{\text{tran}}(R_i)$ of each reader R_i. The system must adapt to these changes dynamically, by adjusting the reader i parameters such as frequency f_i, time slot t_i, and coverage area C_i.

4) Scalability: As the number of readers N increases, the system must efficiently scale while maintaining high throughput and minimizing collisions. We modeled system efficiency $\mathcal{E}$ of our system as follows:

$$\mathcal{E}(t) = \frac{1}{N} \sum_{i=1}^{N} \mathcal{E}(R_i, t), \quad (4)$$

where $\mathcal{E}(R_i, t)$ is the efficiency of each reader, which is a function of collision probability and interference level, as:

$$\mathcal{E}(R_i, t) = \frac{1}{1 + P_{\text{coll}}(R_i, t)} \cdot (1 - I_{\text{total}}(R_i, t)). \quad (5)$$

C. Reader Network Operation

1) RFID Communication: RFID systems typically follow the *Reader-Talk-First (RTF)* protocol, where a reader transmits signals to passive tags, which reflect modulated signals back to the reader. Each reader communicates on a specific frequency f_i at time slot t_i. The system's efficiency is directly related to how well the resources are managed to avoid collisions.

2) Neighborhood Discovery: Each reader R_i must identify neighboring readers within its interference range IR_i. This is achieved by readers periodically broadcasting *My Neighborhood Info* messages D_i, and *Alive* messages A_i, and neighboring readers respond with their operational parameters. A readers neighborhood register $N(R_i)$ is then updated as:

$$N(R_i) = \{R_j | R_j \text{ responds to } D_i\}. \quad (6)$$

The operational state of each neighbor is tracked so that readers can dynamically adjust their communication parameters accordingly. We utilize separate channels for different purposes (control vs. discovery vs. tag reading) to align with Federal Communications Commission (FCC) guidelines and to avoid interference with the primary tag communication channels (902-928 MHz). For Neighborhood Info and Alive messages, we used 929MHz for our control channel, which is close to the upper edge of the ISM band and often less congested. Similarly, we choose 900 MHz for reader discovery messages, utilized by new readers to find a network.

3) Resource Allocation: To minimize interference in the RFID system, readers employ Dynamic Frequency Hopping (DFH) and Frequency/Time Division Multiple Access (F/TDMA). These strategies enable each reader to dynamically allocate communication resources by selecting frequencies and time slots that minimize interference from neighboring readers. The frequency allocation process involves continuously assessing the level of interference across available channels and selecting the frequency that minimizes the cumulative impact of nearby readers. Similarly, time slots are assigned based on the level of contention among neighboring readers, ensuring that transmissions do not overlap in time.

4) Reader State Management: Each reader's neighborhood state can be categorized into one of three states given as $S_i = \{\text{active}, \text{inactive}, \text{interfering}\}$, depending on their current communication actions, the local reader density, $P_{\text{coll}}(R_i, t)$, and $I_{\text{total}}(R_i, t)$. The system continuously updates each reader's state based on real-time system conditions, ensuring a balance in the frequency of updates, thus, avoiding excessive updates and reducing system overhead while improving adaptability.

III. Proposed Methods

A. Neighborhood Discovery and Management

The process of our proposed neighborhood discovery approach begins with each reader R_i broadcasting periodic *My*

Neighborhood Info messages D_i, which includes the reader's ID R_i, current operational parameters (frequency f_i, time slot t_i), and state information (active, inactive, interfering) on the control channel $f_N = 929$ MHz. Neighboring readers R_j respond with their neighborhood info messages D_j, enabling R_i to update its neighborhood register $N(R_i)$ as in (6). **Algorithm 1** outlines the steps for neighborhood discovery and dynamic resource allocation in our proposed system. The exchange of messages allows readers to identify neighboring readers, their respective states, and current operational parameters. The reader-to-reader interference for each pair of readers R_i and R_j is determined by (2). Once neighborhood information is exchanged, each reader dynamically adjusts its communication parameters using DFH and F/TDMA to minimize interference and maximize throughput.

Algorithm 1 Neighborhood Discovery and Resource Allocation

```
Initialize each reader R_i, set f_N = 929 MHz;
while Reader R_i is active do
    Broadcast My Neighborhood Info D_i, receive responses from
    R_j ∈ N(R_i), and update neighborhood register;
    Adjust f_i and t_i {use DFH, F/TDMA};
    Monitor I_total(R_i, t) and adjust C_i;
    Compute collision probability P_coll(R_i, t);
    Periodically broadcast Alive;
    if state change conditions met then
        Adjust reader operational state S_i;
    end if
end while
```

B. Reader Network Discovery

In our approach, the process of integrating a new reader R_{new} into an existing RFID system begins with a *Discovery Request*, initiated on a designated channel $f_d = 900$ MHz. The discovery process, outlined in **Algorithm 2**, ensures seamless integration while minimizing interference with existing readers. The new reader R_{new} broadcasts its request containing its reader ID, name, and configuration. This request is aimed at identifying neighboring readers within its coverage area. Each neighboring reader $R_j \in N(R_{\text{new}})$ responds with an acknowledgment, providing their respective network and configuration information. Based on these responses, the new reader selects a network N_{select}. Upon selecting N_{select}, the new reader updates its internal registers (Shared Medium, Neighborhood, Network, and Antenna) and transitions to an active operational state.

C. Collision Detection and Avoidance

Each time the neighborhood discovery process is completed, each reader i calculates the collision probability $P_{\text{coll}}(R_i)$ based on real-time interference and adjust its operational state to avoid collisions. Through this dynamic adjustment, readers can effectively back off or change frequencies to minimize contention. The overall system collision probability is therefore given by

$$P_{\text{coll}} = 1 - \prod_{i=1}^{N}(1 - P_{\text{coll}}(R_i)). \tag{7}$$

The system continuously monitors this value and dynamically adjusts the communication parameters to avoid interference and maintain optimal performance. The overall system throughput is a function of the collision probability and the total interference experienced by each reader is calculated from (4) and (5).

Algorithm 2 Reader Network Discovery

```
Initialize R_new, set f_d = 900 MHz;
Broadcast discovery request
r_new = {ID_i, Reader Name_i, Configuration};
Collect responses
r_i = {ID_i, Reader Name_i, Network ID, Configuration} from
readers R_j ∈ N(R_new);
Select network N_select;
Update Shared Medium, Neighborhood, Network, and Antenna
tables for R_new;
Transition state of R_new to active;
```

IV. Experimental Study and Discussions

A. Setup and Configuration

The experimental setup for evaluating our proposed approach utilized the USRP N210 SDR hardware platform, an OctoClock 2990A for synchronization, a Cisco network switch, and a high-performance computer. The USRP N210s, equipped with daughterboards to handle the RFID frequency band, emulate RFID readers transmitting and receiving signals using dynamic frequency hopping to mitigate interference. Real-time data was captured and processed using GNU Radio Companion, which interfaced directly with the USRPs. The OctoClock 2990A provided precise synchronization by distributing a 10 MHz clock signal and PPS timing signal to each USRP, reducing the probability of reader collisions. A Cisco gigabit Ethernet switch enabled seamless data transfer between the SDRs and the computer, ensuring low latency and high throughput for real-time control and data acquisition. Custom scripts further facilitate communication management and data logging for comprehensive analysis.

B. Experiment Design

This experiment was designed to evaluate the performance of our proposed method for decentralized neighborhood discovery and management in dense RFID environments, with an emphasis on minimizing collisions and enhancing system throughput. To emulate a realistic RFID deployment, multiple USRP N210 SDRs with VERT 900 antennas are utilized as RFID readers, while passive RFID tags are strategically placed to represent varying levels of tag density. Our algorithm's ability to coordinate multiple readers and manage simultaneous tag readings—critical for effective neighborhood discovery—is tested under different network conditions. The experimental setup includes key parameters such as the number of active readers, tag density, and transmission power. The experimental design also incorporated different reader and tag configurations to assess the scalability and robustness of the proposed decentralized discovery and management method, particularly in scenarios where multiple readers operate simultaneously.

C. Experimental Results

We execute our schemes as an additional layer on top of the GEN-2 protocol implemented with USRP, and compare the proposed system to the scenario where the GEN-2 works alone on the same device. A snapshot of updated consolidated Neighborhood, Network, and Antenna registers is shown in Tables I, II, III for readers 2 and 3. Fig. 2 summarizes the performance improvements offered by our proposed method.

TABLE I
READER NEIGHBORHOOD REGISTER

Entry	Reader ID	State	Protocol	Frequency	Timeslot	LHF[1]
1	2	Active	F/TDMA	920 MHz	2	31s
2	3	Active	CSMARA	922 MHz	5	50s

[1] Last Heard From (LHF): the time difference between the last Alive message received and now.

TABLE II
NETWORK INFORMATION REGISTER

Entry	Network ID	Leader ID	Antenna IDs	Last Updated Time
1	23456789012345	2	0, 1	2024-09-13 15:00:00
2	34567890123456	3	0, 1	2024-09-13 15:30:00

TABLE III
ANTENNA INFORMATION REGISTER

Entry	Antenna ID	State	Associated Network ID	Last Updated Time
1	0	Active	23456789012345	2024-09-13 14:30:00
2	0	Active	23456789012345	2024-09-13 15:30:00
3	1	Active	34567890123456	2024-09-13 14:30:00
4	1	Active	34567890123456	2024-09-13 15:30:00

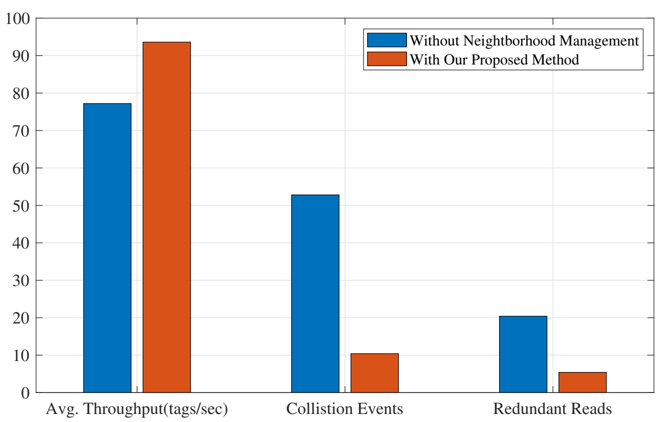

Fig. 2. Performance comparison with and without our approach

D. Analysis and Discussion

The proposed *Decentralized Neighborhood Discovery and Management* method significantly improves the performance of dense RFID systems. Compared to a system without neighborhood management on USRP, our method leads to: (i) Higher Throughput: Tag detection rates increase from 77.2 tags/sec to 93.6 tags/sec, demonstrating that the decentralized approach optimizes system efficiency by minimizing interference and allowing more frequent successful reads. (ii) Fewer Collision Events: Collisions drop from 52.8 to 10.4 with the decentralized method, as readers dynamically adjust their operations to avoid interference, ensuring smooth operation in dense environments. (iii) Reduced Redundant Reads: The number of unnecessary reads decreases from 20.4 to 5.4, reflecting more efficient use of system resources as readers coordinate to prevent redundant operations.

V. CONCLUSIONS

In this paper, we introduced a decentralized approach for neighborhood discovery and management in dense RFID systems to address reader-to-reader interference and resource allocation. By utilizing dynamic adjustments to communication parameters such as frequency and time slots, the proposed method optimizes system throughput, reduces collisions, and enhances the reliability of tag reads. This approach improves the scalability and performance of RFID systems in high-density environments, providing a foundation for future research in advanced interference management and optimization techniques in real-world implementation.

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