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Optimizing Adaptive Power Control for Enhancing Robustness in RFID Sensing

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***Abstract*—In dense RFID systems, power control provides an effective means for maintaining communication efficiency and preventing reader-to-reader and reader-to-tag interference. Traditional RFID systems often operate at fixed power levels, which can lead to communication bottlenecks and inefficient tag reads in dynamic environments. This paper proposes an adaptive power control technique to improve the system performance by dynamically adjusting the transmit power based on environmental conditions, tag distance, and network congestion. Simulations and experimental results demonstrate that the proposed approach improves tag read rates, reduces interference, and enhances system robustness in dense environments.**

***Index Terms*—RFID, adaptive power control, interference management, robust RFID sensing, RFID sensing performance.**

I. INTRODUCTION

Radio Frequency Identification (RFID) technology has been widely adopted across various industries for object tracking [1], inventory management [2], and wireless sensing applications [3], [4]. As the deployment of RFID systems expands to dense environments, where multiple RFID readers and tags operate in close proximity, interference management and efficient power control become critical challenges [5]–[8]. In such settings, the performance of RFID systems can degrade significantly due to reader-to-reader interference (RRI), reader-to-tag collisions, and inefficient power usage, which in turn results in missed tag reads, lower throughput, and reduced system reliability. This issue arises from the fixed transmission power levels traditionally used by RFID readers in a particular operation period. In dense deployments, such fixed power approach leads to excessive interference, particularly when multiple readers simultaneously interrogate tags within overlapping interrogation zones [9]. Furthermore, fixed power allocation fails to account for varying tag distances, environmental conditions, and network dynamics. As a result, the system could experience unnecessary power consumption, inefficient frequency utilization, and higher collision rates [10].

In this paper, we propose adaptive power techniques to address these challenges and enhance the robustness of RFID sensing in dense environments. The proposed methodology dynamically adjusts the transmit power of each reader based on real-time environmental conditions, reader-to-reader interference, and tag location. By leveraging adaptive power control algorithms, our approach minimizes interference, reduces power consumption, and optimizes tag read performance while minimizing overlap in interrogation zones in dense RFID environments

Our framework continuously monitors interference levels, tag response rates, and network conditions to enable adaptive power control. Readers dynamically adjust their transmission power to maintain communication quality while ensuring minimal interference with neighboring readers. The proposed method is built upon fundamental principles such as Carrier Sense Multiple Access (CSMA) to ensure that communication resources are allocated efficiently across readers and tags. Through simulations and real-world experiments, we demonstrate that our adaptive power techniques lead to significant improvements in system throughput, power efficiency, and overall tag read reliability.

The remainder of this organized as follows. We provide the problem statement in Section II and describe the proposed schemes in Section III. Section IV present our experimental study and Section V concludes this paper.

II. PROBLEM DEFINITION AND PRELIMINARY

In dense RFID systems, multiple readers and tags operate simultaneously in close proximity, leading to several key challenges, particularly in reader-to-reader interference (RRI), inefficient power allocation, and collisions [8], [11], [12]. The traditional fixed power transmission systems are inadequate to deal with dynamic and dense environments. For brevity, consider a set of readers $\mathbf{R} = \{R_1, R_2, ..., R_n\}$ and a set of RFID tags $\mathbf{T} = \{T_1, T_2, ..., T_m\}$ within a given environment. Each reader R_i operates at a power level P_i, communicates with the tags in its interrogation zone, and experiences interference from other readers $R_k \in \mathbf{R},\ k \neq i$. Our goal is to adjust the power levels P_i dynamically to minimize interference and reader-to-tag collisions while ensuring efficient communication with the tags. Tag-to-tag collision, while also present in some RFID systems, is outside the scope of this work.

1) Interference and Collision Probability: Each reader R_i interrogates a subset of tags within its range. The signal strength $S_{i,j}(t)$ received by tag T_j from reader R_i is:

$$S_{i,j}(t) = \psi \cdot P_i(t) \cdot d_{i,j,\psi}^{-\alpha}, \tag{1}$$

where $P_i(t)$ is the transmit power of reader R_i at time t, $d_{i,j,\psi}$ is the distance between reader R_i, and tag T_j, α is the path loss exponent, and ψ accounts for multipath components.

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For successful communication, the signal strength $S_{i,j}$ must exceed a minimum threshold S_{thresh}, as:

$$S_{i,j} \geq S_{\text{thresh}}. \tag{2}$$

Interference between readers R_i and R_k occurs when both operate on the same frequency or on frequencies in close proximity. The interference power $I_{i,k}$ between the two readers is given by:

$$I_{i,k}(t) = P_k(t) \cdot d_{i,k}^{-\beta} \cdot I(f_i, f_k, t), \tag{3}$$

where $d_{i,k}$ is the distance between readers R_i and R_k, $I(f_i, f_k, t)$ is the frequency overlap factor, and β is the interference path loss exponent. It follows that the total interference contributions from all neighboring readers $R_k \in N(R_i)$ at reader R_i can be evaluated as:

$$I_{\text{sum}}(R_i, t) = \sum_{R_k \in N(R_i)} I_{i,k}(t). \tag{4}$$

If $I_{\text{sum}}(R_i, t)$ exceeds a predefined threshold, the reader can adjust its transmit power to reduce interference. This interference affects the probability of collision. The collision probability $P_{\text{col}}(R_i)$ for reader R_i is given by:

$$P_{\text{col}}(R_i) = 1 - \prod_{k \neq i} \left(1 - P_{\text{int}}(R_i, R_k)\right) \cdot \prod_{j} \left(1 - P_{\text{int}}(R_i, T_j)\right), \tag{5}$$

where $P_{\text{int}}(R_i, R_k)$ represents probability of the interference between readers R_i and R_k, and $P_{\text{int}}(R_i, T_j)$ represents the probability of interference between reader R_i and tag T_j.

III. PROPOSED METHODOLOGY

A. *Adaptive Power Control*

In dense RFID systems, readers can dynamically adjust their power levels $P_i(t)$ over time to ensure effective communication with tags while minimizing interference with neighboring readers. Our proposed power control mechanism, **Algorithm 1** is based on real-time feedback from the environment, to adjust power according to the observed signal-to-noise ratio (SNR) and interference level. The adaptive power control strategy aims to minimize interference while ensuring the received signal strength $S_{i,j}$ at tag T_j is above the required minimum threshold S_{thresh}. This can be formulated as the following optimization problem:

$$\min_{P_i(t)} I_{\text{sum}}(R_i, t), \quad \text{s.t. } S_{i,j}(t) \geq S_{\text{thresh}}, \ \forall T_j \in \mathbf{T}, \tag{6}$$

where the signal strength $S_{i,j}(t)$ is given by (1).

Our power control update rule is derived from the observed interference and signal level. By using a proportional control mechanism, the power is adjusted iteratively as follows:

$$P_i(t+1) = P_i(t) + \eta \cdot \left(S_{\text{thresh}} - S_{i,j}(t)\right), \tag{7}$$

where η is the adaptation rate, controlling how fast the power level is adjusted based on the difference between the actual and required signal strength. Each reader dynamically adjusts its transmission power based on tag distance, interference management, and network congestion, detailed as follows.

1) Tag Distance: Power is adjusted based on the estimated distance to the farthest tag in the reader's interrogation zone. Tags closer to the reader require less power, while distant tags necessitate higher power levels, as:

$$P_i(t) = \frac{S_{\text{thresh}}}{G_t \cdot G_r} \cdot \left(\frac{4\pi d_i}{\lambda}\right)^2 + \phi, \tag{8}$$

where d_i is the distance to the farthest tag, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, λ is the wavelength of the signal, and ϕ is the power offset.

2) Interference Management: Interference between readers is a critical challenge in dense RFID systems. The proposed approach continuously monitors the interference levels $I_{\text{sum}}(R_i, t)$ for each reader i and adjusts its power to reduce the impact of RRI.

3) Network Congestion: Power adjustments are made based on real-time network conditions, such as the number of active readers and tags. If network congestion level increases, power should be reduced to minimize collisions.

Algorithm 1 Adaptive Power Control for RFID Readers

```
Initialize reader $R_i$ with $P_i(0)$, Reader Rate Threshold $R_{\text{threshold}}$, signal threshold $S_{\text{thresh}}$, adaptation rate $\eta$;
while Reader $R_i$ is active do
    Measure signal $S_{i,j}(t)$ from each tag $T_j$ and total interference $I_{\text{sum}}(R_i, t)$;
    if $S_{i,j}(t) < S_{\text{thresh}}$ and Read rate $< R_{\text{threshold}}$ then
        Increase power: $P_i(t+1) = P_i(t) + \eta \cdot (S_{\text{thresh}} - S_{i,j}(t))$;
    else if $S_{i,j}(t) \geq S_{\text{thresh}}$ then
        Decrease power: $P_i(t+1) = P_i(t) - \eta \cdot (S_{i,j}(t) - S_{\text{thresh}})$;
    end if
    Broadcast adjusted power: $P_i(t+1)$ to $R_j \in N(R_i)$;
    Monitor interference $I_{\text{sum}}(R_i, t)$, compute $P_{\text{col}}(R_i)$;
    if state change conditions met then
        Adjust reader operational state $S$;
    end if
    if $I_{\text{sum}}(R_i, t) > I_{\max}$ and Read rate $< R_{\text{threshold}}$ then
        Re-adjust power: $P_i(t+1) = P_i(t) - \eta \cdot I_{\text{sum}}(R_i, t)$;
    end if
end while
```

B. *Dynamic Reader State Transitions*

Readers in the RFID system transition between different operational states based on the observed network conditions. Our system defines three primary states: $S \in \{$reading, idle, update coverage$\}$. The state transition depends on local reader density, collision probability, and total interference experienced by the reader. Thus, by dynamically adjusting power, the proposed system ensures readers maintain optimal operational states, minimizing collisions and maximizing throughput.

IV. EXPERIMENTAL STUDY AND DISCUSSIONS

A. *Reader Design*

The RFID readers used in this study incorporate an adaptive power control algorithm that dynamically adjusts transmission power based on environmental conditions. Each reader monitors the signal strength received from tags and the interference caused by neighboring readers. When the signal strength falls below a certain threshold, the reader increases its transmission power to ensure reliable tag detection. Conversely, when interference exceeds a predefined limit, the reader reduces its power to avoid collisions with neighboring readers. This adaptive approach allows each reader to maintain an optimal detection range while minimizing energy consumption and interference in dense RFID environments. The readers have a maximum transmission power of 30 dBm and a minimum power of 10 dBm, which satisfies the regulation of the Federal Communications Commission (FCC) and provides sufficient flexibility for efficient operation in various conditions.

B. Simulation Parameters

The simulation environment consists of 20 readers and 500 tags randomly distributed across a 150×150 meters as shown in Fig. 1. The simulation runs for 3,000 time steps, during which readers continuously adjust their power levels based on signal strength and interference. Key parameters include a path loss exponent of 2 for both signal strength and interference, a signal-to-noise ratio threshold of 0.5, and an adaptation rate of 0.05, which determines how quickly the readers adjust their power levels. The readers aim to maintain a maximum detection range of 6 meters while minimizing interference with neighboring readers. An interference threshold of 1.0 is used to trigger power reductions when interference becomes too high. These parameters simulate the behavior of RFID readers in real-world conditions where multiple readers and tags operate simultaneously.

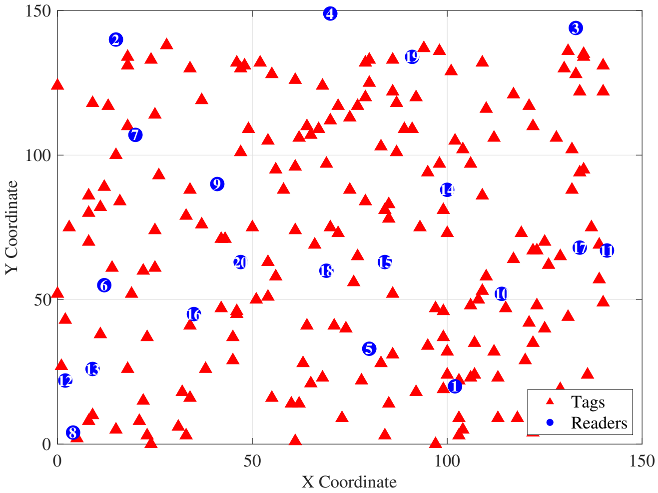

Fig. 1. The simulation scenario of reader-tag placement in a square region with adaptive power control.

C. Evaluation Metrics

The performance of the RFID system is evaluated using several key metrics. First, the **average detection range** measures the mean distance at which readers successfully detect tags during the simulation, indicating overall coverage. The average detection range D_r is calculated as:

$$D_r = \frac{1}{N \times T} \sum_{i=1}^{N} \sum_{t=1}^{T} D_{i,t}, \tag{9}$$

where N is the number of readers, T is the number of time steps, and $D_{i,t}$ is the detection range of reader R_i at time t. Next, the **percentage of time achieving the desired range**, A_d, calculates how often each reader can maintain its target detection range of 6 meters, providing insight into the system's reliability. This is calculated as:

$$A_d = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{t_i}{T} \right) \times 100, \tag{10}$$

where t_i is the number of time steps during which the reader was able to detect tags within the desired range. **Power efficiency**, denoted by E_p, measures how well each reader conserves energy while maintaining satisfactory performance. It is defined as:

$$E_p = \frac{1}{N \times T} \sum_{i=1}^{N} \sum_{t=1}^{T} \frac{D_{i,t}}{U_{i,t}}, \tag{11}$$

where $D_{i,t}$ is the detection range and $U_{i,t}$ is the power utilization of reader R_i at time t. Finally, **interference levels** track the amount of interference experienced by each reader from neighboring readers, which directly impacts detection accuracy and power consumption.

D. Results and Analysis

The performance of the proposed adaptive power control algorithm is evaluated using the evaluation metric discussed earlier. The results demonstrate the effectiveness of the algorithm in optimizing power consumption, maintaining detection range, and minimizing interference.

1) Power Levels: The average power levels for most readers remained between 10 dBm and 15 dBm as shown in Fig. 2, with a peak at 20 dBm for reader 7, followed by reader 18 with a peak at 16 dBm. This indicates that the algorithm effectively regulates power, avoiding excessive energy consumption. The stability of power levels across readers highlights the algorithm's ability to balance power requirements based on environmental conditions, ensuring that readers use sufficient power to maintain detection range while minimizing energy waste.

2) Detection Range: The detection range for the readers varied between 2 meters and 7 meters (see Fig. 2). Reader 14 exhibited a higher detection range, reaching close to 7.5 meters, while others maintained a more moderate range. This variability demonstrates the algorithm's adaptability to different environments. Readers positioned closer to tags or in areas with less interference were able to achieve higher detection ranges without requiring excessive power. This adaptability is a key feature of the algorithm, ensuring that readers optimize their performance based on their surroundings.

3) Interference Levels: The average interference levels across all readers remained below 3 (also see Fig. 2), indicating effective collision avoidance. Even readers with higher detection ranges did not experience significant increases in interference, suggesting that the algorithm successfully manages power to prevent collisions. This low level of interference is crucial in dense RFID environments, where multiple readers operate simultaneously. The ability of the algorithm to minimize interference while maintaining detection range and power efficiency indicates its robustness in managing multiple readers in a confined space.

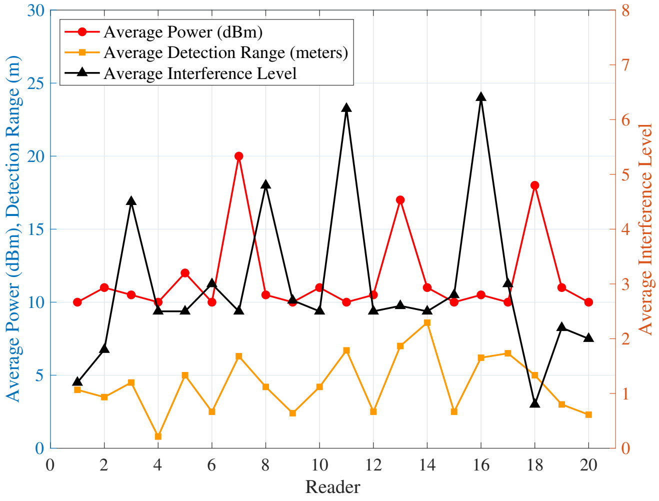

Fig. 2. Average power levels, detection range, and interference levels for the readers.

4) Power Efficiency: Power efficiency, defined as the ratio of detection range to power consumption, varied significantly among readers, as shown in Fig. 3. Readers such as 11, 14, 16, and 17 achieved power efficiencies above 0.5, reflecting highly efficient operation, while others, such as Reader 4, exhibited lower efficiency, around 0.1. This variation suggests that the algorithm adapts to different environmental challenges. Readers in favorable conditions, such as closer proximity to tags and lower interference, operate with higher efficiency.

5) System Throughput: System throughput, measured as the percentage of time readers achieved the desired detection range (6 meters), was consistently maintained across the simulation. The combination of low interference, stable power consumption, and sufficient detection range suggests that the system operates with high reliability, achieving a balance between performance and energy consumption. Our technique achieved an average throughput of 90% in the simulations.

V. CONCLUSIONS

This paper presented a novel adaptive power control technique for RFID sensing, addressing the limitations of static power settings in dense environments. The proposed method enhances system robustness and energy efficiency by continuously adjusting transmission power based on tag distance, interference levels, and network congestion. The simulation results demonstrated that the proposed algorithm can effectively reduce interference and optimize power usage in a dense RFID environment. It offers a promising scalable solution for improving dense RFID system performance in real-world applications with many RFID readers and high population of RFID tags.

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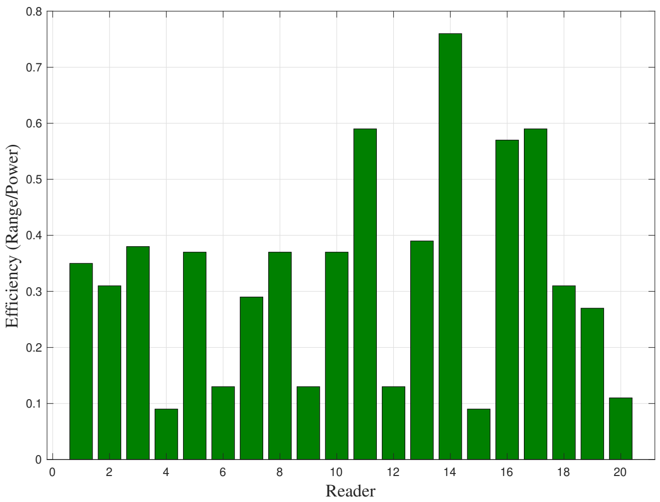

Fig. 3. Power efficiency for each reader.

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