Postprint: Research on Parallel-Identifiable UHF RFID Anti-Collision Algorithms

Authors: He Yigang, She Peiliang, Zuo Lei, Zhang Chaoqun

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Abstract

This work investigates the problems of low system throughput and identification rate in conventional Dynamic Frame Slotted Aloha (DFSA) multi-tag anti-collision algorithms, and proposes a UHF RFID anti-collision algorithm (OVSF-DFSA) supporting parallel identification. The algorithm integrates Code Division Multiple Access (CDMA) technology employing Orthogonal Variable Spreading Factor (OVSF) codes as spreading codes with the Dynamic Frame Slotted ALOHA (DFSA) protocol, thereby overcoming the limitation of traditional algorithms that can only identify a single tag per time slot and realizing a transition from tag collisions to code collisions. Through theoretical analysis and simulation experiments, the performance characteristics of the proposed algorithm are examined in terms of system throughput, total number of time slots, and system identification rate. Simulation results demonstrate that when the frame length fs>2 and OVSF code length m>2, and the number of tags exceeds 200, the system throughput of the OVSF-DFSA algorithm is m times that of the DFSA algorithm. Furthermore, compared with DFSA, MS-DFSA, and PIGDFSA algorithms, the OVSF-DFSA algorithm exhibits superior performance in the aforementioned metrics.

Full Text

Research on a Parallelizable Identification Anti-Collision Algorithm for UHF RFID

He Yigang†, She Peiliang, Zuo Lei, Zhang Chaoqun
(School of Electrical Engineering & Automation, Hefei University of Technology, Hefei 230009, China)

Abstract: This paper addresses the low system throughput and identification rate problems inherent in traditional dynamic frame slotted Aloha (DFSA) multi-tag anti-collision algorithms by proposing a parallelizable identification

UHF RFID anti-collision algorithm (OVSF-DFSA). The algorithm combines code division multiple access (CDMA) technology using orthogonal variable spreading factor (OVSF) codes as spreading codes with the dynamic frame slotted ALOHA (DFSA) protocol, breaking the limitation of recognizing only one tag per single time slot and transforming tag collisions into code collisions. Based on theoretical analysis and simulation experiments, this paper investigates the algorithm' s performance in terms of system throughput, total time slots, and system identification rate. Simulation results demonstrate that when the frame length fs > 2 and OVSF code length m > 2, and when the number of tags exceeds 200, the system throughput under the OVSF-DFSA algorithm is m times that of the DFSA algorithm. Compared with DFSA, MS-DFSA, and PIGDFSA algorithms, OVSF-DFSA exhibits superior performance across these metrics.

Keywords: RFID; parallel recognition; code division multiple access; OVSF-DFSA

0 Introduction

In RFID systems with dense tag populations, communication between readers and tags suffers from data (tag) collision problems that degrade system performance metrics such as identification rate and efficiency. The fundamental cause of multi-tag identification collisions is conflict arising from shared wireless channels; consequently, the purpose of tag anti-collision algorithms is to control multiple tags' access to the wireless channel, thereby reducing collision rates among tags.

Currently, four primary technologies address wireless channel sharing conflicts: Space Division Multiple Access (SDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), and Time Division Multiple Access (TDMA) [1]. Due to the low power consumption and limited storage capacity of passive tags, RFID anti-collision algorithms primarily employ TDMA technology. TDMA-based algorithms fall into two categories: tree-based algorithms (deterministic algorithms) [2, 3] and ALOHA algorithms (randomized algorithms) [4]. Tree-based algorithms select tags for communication based on unique tag IDs, which creates excessive reader overhead and long identification times as tag populations grow rapidly, making them unsuitable for large-scale dense tag RFID systems. ALOHA algorithms, by contrast, are widely adopted due to their simplicity and ease of implementation. However, in ALOHA and its improved variants such as Frame Slotted ALOHA (FSA), Dynamic Frame Slotted ALOHA (DFSA) [5], and Grouped Dynamic Frame Slotted ALOHA (GDFSA) [6], a reader can identify at most one tag per time slot, resulting in low system throughput.

Recent research has sought to overcome this limitation. An improved GDFSA algorithm achieved stable maximum system throughput between 34.6% and 36.8% [7]. A frame slotted ALOHA anti-collision algorithm based on Markov slot state modeling introduced continuous slot prediction mechanisms and adaptive hashing schemes, effectively reducing idle slots and maintaining system throughput above 60% [8]. Further development of the Grouped Adaptive Allocation Slot ALOHA (GAAS) algorithm allowed readers to directly skip idle and collision slots, maintaining system throughput above 71% [9]. Nevertheless, these approaches failed to break the fundamental limitation of identifying only one tag per slot, preventing fundamental improvement in system throughput. In contrast, literature [10, 11] introduced blind source separation technology to achieve the breakthrough of parallel identification of multiple tags within a single slot. For instance, literature [12] integrated FastICA technology into the GDFSA algorithm to propose the parallelizable identification PIGDFSA algorithm, which stabilized system throughput between 92% and 97.3%. However, these algorithms impose high requirements on the number of reader antennas.

In wireless communications, CDMA technology can process multiple transponders simultaneously within the same time period, but its standalone application in RFID systems is constrained by tags' low power consumption and limited storage capacity. Literature [13, 14] proposed a parallelizable DFSA-OC RFID system combining CDMA technology based on OVSF orthogonal variable spreading codes with the DFSA protocol, though it employed the Schoute algorithm for estimating the number of unidentified tags, which does not adapt well to dynamic changes in tag populations. Due to hardware limitations on spreading code length m and communication bandwidth, this paper combines orthogonal variable spreading factor CDMA technology with the dynamic frame slotted anti-collision protocol (DFSA). Since tags within the same slot carry different spreading codes, the reader can identify multiple tags in parallel within a single slot. By estimating the number of unidentified tags and dynamically adjusting the spreading code length, the system balances RFID performance and complexity while improving maximum throughput, reducing identification time, and enhancing system identification rates.

1.1 OVSF-DFSA System

CDMA technology is widely applied in various wireless communication scenarios, enabling multiple tags to access information simultaneously within the same time period. To reduce collision probability among multiple tags within a single slot in traditional ALOHA algorithms (DFSA) and improve system throughput and identification rate, this paper proposes combining CDMA with TDMA technology in UHF RFID systems. This approach completely eliminates tag collisions inherent in current single-channel UHF RFID systems while allocating a time slot to each tag as in the DFSA protocol, with tags in the same slot distinguished by different OVSF spreading codes. We designate this system as the OVSF-DFSA system. The system comprises a downlink spread spectrum orthogonal coding link (not discussed herein) and an uplink spread spectrum orthogonal parallel response link (shown in Figure 1), with the uplink synchronized by the downlink and tags synchronized by the reader.

[Figure 1: see original paper]

1.2 Orthogonal Variable Spreading Factor (OVSF) Codes

In CDMA technology, spreading code selection affects the system's anti-multiple-access interference capability. Pseudo-random sequences (PN) with good auto-correlation properties are typically selected as spreading codes, such as MS codes [15], Gold codes [16], and OVSF codes. Gold codes cannot despread downlink spectrum extensions and are only suitable for active tags. OVSF codes, due to their excellent orthogonality and variable-length properties that support multi-rate communication services, are widely applied in CDMA systems. OVSF codes can be generated recursively from Hadamard matrices [17] and exhibit a tree structure, as shown in Figure 2. Each OVSF code is uniquely identified by C(k,n), where k represents the layer number and n represents the position number within the layer. All codes on the same layer of the tree are mutually orthogonal. Each code has length 2^k, with practical applications depending on communication protocol selection and hardware resource constraints. The system can only allocate OVSF codes to each transponder from the same layer of the code tree.

[Figure 2: see original paper]

1.3 OVSF-DFSA System Anti-Collision Principle and Algorithm Example

In the OVSF-DFSA system downlink (the communication process from reader to tags, not shown in Figure 1), the reader first transmits an initialization command containing frame length fs and OVSF code length m to the tags. Upon receiving the query command, tags extract parameters fs and m, then randomly select an OVSF code from a pre-established OVSF code table library to spread-spectrum modulate their ID information. In the OVSF-DFSA system uplink, as shown in Figure 1, when the reader receives responses from tags, it must decode the signals. Based on the OVSF code length parameter m sent by the tags, the reader queries its OVSF code table tree to obtain all spreading codes of length m, then performs spread-spectrum demodulation to acquire the ID information of tags to be identified [15].

Figure 3 illustrates the collision prevention algorithm in the OVSF-DFSA system for identifying large-capacity dense tag populations, which may encounter three situations (initialized with fs=8, m=4):

a) Only one tag responds within a single slot: The reader successfully identifies this tag, just as in the DFSA protocol, as shown in slot 1 of Figure 2.

b) n ($n \geq 2$) tags respond in the same slot: When these n tags carry identical OVSF codes, code collision occurs and identification fails, as shown with tags 2, 3, and 4 in slot 2 of Figure 2. When the n tags carry different

OVSF codes, they can be successfully identified, as shown with tags 6 and 7 in slot 4 of Figure 2.

c) No tags respond in a slot: This constitutes an idle slot, as shown in slots 3, 6, 7, and 8 of Figure 2.

The OVSF-CDMA algorithm breaks the limitation of traditional DFSA algorithms that can only identify one tag per slot, thereby transforming tag collisions into code collisions. Without code collisions, a single slot can identify up to m tags, and a frame can identify up to m×fs tags. On one hand, when the number of tags to be identified N and frame length fs are fixed, larger OVSF code length m reduces code collision probability within a single slot, yielding higher system throughput. On the other hand, larger OVSF code length m consumes more frequency (channel) resources and imposes higher demands on hardware computational capability and storage capacity, though typically $m < 128$ satisfies application requirements.

In practical UHF RFID systems, the number of tags to be identified is unknown and variable. To achieve optimal throughput, both frame length fs and OVSF code length m should be adjusted dynamically. However, due to limited computational capacity of RFID tags, m remains constant while frame length fs must adapt in real-time based on the number of unidentified tags: 1) When tag count n is large, a larger frame length fs improves system throughput U, reduces system overhead, and decreases identification time; 2) When tag count n is small, a smaller frame length fs enhances system throughput E, reduces total time slots, and shortens identification time.

1.4 Estimation Method for Unidentified Tag Count n

CDMA-DFSA requires the reader to estimate the number of unidentified tags within the identification range before initiating a new round of identification, thereby dynamically adjusting frame length to improve channel utilization and throughput. Current estimation methods for large-capacity dense tag populations include the Schoute algorithm, Vogt algorithm, Cha algorithm, and MAPP algorithm. The Vogt algorithm employs Chebyshev' s inequality to minimize the gap between actual statistical results and theoretical calculations, offering higher accuracy and stable error, making it suitable for estimating unidentified tags in this work.

2 OVSF-DFSA Algorithm Steps

Under the ISO/IEC 18006-6 protocol, the specific steps of the OVSF-DFSA anti-collision algorithm based on CDMA technology for parallel identification of multiple tags are as follows:

a) The reader sends a query command "Query" (containing frame length parameter fs and OVSF code length parameter m) to all tags entering the identification range, initiating an inventory cycle, and tags enter the ready state.

b) Upon receiving the "Query" command, tags extract parameters fs and m. Each tag randomly generates a slot number Si (Si [1, fs]) and loads it into its slot counter Sc.

c) The reader sends an acknowledgment command "ACK" to tags in the ready state. All tags with slot counter Sc=0 respond and randomly generate a code index number R (R [1, m]) to select a corresponding OVSF code from the pre-established OVSF code table. Each tag uses its randomly selected OVSF code to spread-spectrum modulate its ID data information before transmitting to the reader.

d) The reader decodes the signals from responding tags. Tags experiencing code collision return to step c) to await the next round of identification. For tags without code collision, the reader demodulates their spread-spectrum signals to obtain their ID information. After completing the round, the reader counts idle slots c0, successful slots cs, and collision slots cc to estimate the number of unidentified tags and adjust frame length fs accordingly.

e) The reader begins a new round of identification by sending the query command "QueryRep," decrementing the slot counter Sc of unidentified tags by 1, then jumping to step 3) until all tags are identified.

3.1 Theoretical Derivation

In RFID systems, system throughput (or throughput rate) refers to the ratio of successfully identified tags to frame length [9], representing the expected number of tags successfully identified per slot and serving as a crucial parameter reflecting anti-collision algorithm performance. OVSF-DFSA algorithm throughput calculation is complex due to multiple tags being identifiable per slot. Assuming N unidentified tags in the RFID system and OVSF spreading code length m (providing m distinct OVSF codes), the probability of n tags being assigned different OVSF codes in a single slot is given by:

$$P(n,m) = \frac{m!}{(m-n)!} \cdot \frac{1}{m^n}$$

From the DFSA protocol, the probability of n tags selecting the same slot is:

$$P(n|N,fs) = \binom{N}{n} \left(\frac{1}{fs}\right)^n \left(1 - \frac{1}{fs}\right)^{N-n}$$

Combining these, the probability of n tags being successfully identified is:

$$P_{success}(n) = P(n|N, fs) \times P(n, m)$$

In any given slot, the reader can identify at most min(m, N) tags, yielding the system throughput expectation for OVSF-DFSA algorithm:

$$E(N, fs, m) = \sum_{n=1}^{\min(m,N)} n \cdot P_{success}(n)$$

When m=1, this simplifies to the classic DFSA algorithm:

$$E(N, fs, 1) = \frac{N}{fs}\left(1 - \frac{1}{fs}\right)^{N-1}$$

Taking the derivative with respect to N and setting it to zero yields the optimal frame length N = fs, with maximum throughput approaching 0.3681 as $N \to \infty$.

When m=2, the expression becomes:

$$E(N, fs, 2) = \frac{N}{fs}\left(1 - \frac{1}{fs}\right)^{N-1} + \frac{N(N-1)}{fs^2}\left(1 - \frac{1}{fs}\right)^{N-2}$$

Differentiating and solving reveals the maximum throughput is approximately 0.840 when fs > 2.

For m > 2, the calculation becomes more complex. Assuming fs > 2, the partial derivative' s zero point occurs at N = m×fs, yielding maximum throughput:

$$\lim_{N\to\infty} E(N, fs, m) = m \times 0.3681$$

Thus, the theoretical throughput of OVSF-DFSA is approximately m times that of classic DFSA.

3.2 Simulation Results and Analysis

To evaluate CDMA-DFSA algorithm performance, we compare it with classic DFSA, MS-DFSA, and PIGDFSA algorithms in terms of system throughput, total reader time slots, and system identification rate. Simulations were conducted on MATLAB 2014 under Windows 7 with hardware configuration: i5-4590 CPU at 3.30 GHz, 4 GB RAM, 64-bit.

3.2.1 System Throughput Simulation Results

Based on theoretical analysis from equations (8), (9), (17), and (19), Figure 4 [Figure 4: see original paper] illustrates the relationship between maximum system throughput and frame length fs and OVSF code length m. In theoretical calculations, fs takes values {2^s | s=2,3,···,10} and m takes values {2^k | k=0,1,···,7}. For fixed fs, throughput increases with m; for fixed m (except m=1), throughput decreases with fs. When m=1, OVSF-DFSA degrades to classic DFSA, stabilizing throughput at 0.3681. When m=128 with fs=1024, throughput drops sharply because few tags are randomly assigned to each slot, failing to demonstrate the advantage of code collision over tag collision.

In practical experiments, the reader initializes frame length fs=8. OVSF-DFSA uses m=32, MS-DFSA uses M-code length m=32, and PIGDFSA uses m=8 antennas. Tags are uniformly distributed, starting from 20 and increasing to 1000 in steps of 50. As shown in Figure 5 [Figure 5: see original paper], when tag count exceeds 200, GDFSA throughput is 0.354, approaching the theoretical limit of 0.3681 but unable to exceed 1 due to single-tag-per-slot limitation. PIGDFSA, based on blind source separation, can identify up to m tags per slot but is limited by antenna count, achieving throughput between 2.53 and 4.47 with high volatility. M-DFSA and OVSF-DFSA, based on CDMA technology, maintain stable throughput for tag counts above 200, with OVSF-DFSA throughput (11.262) being 5.03 times that of SM-DFSA (2.238) and 31.81 times that of classic DFSA (0.354), approaching the theoretical value of m=32 times.

[Figure 4: see original paper] [Figure 5: see original paper]

3.2.2 Total Time Slots Simulation Results

Total time slots represent the sum of idle slots, successful slots, and collision slots required for the reader to identify all tags, inversely proportional to throughput and reflecting system performance. Experiments vary m in {2^k | k=0,1,···,7} and tag count from 50 to 1000 in steps of 50. As shown in Figure 6 [Figure 6: see original paper], classic DFSA (m=1) requires 3140 slots to identify all tags. With m=2, this decreases to 1627 (48.18% reduction). With m=128, only 2850 slots are needed (90.76% reduction), benefiting from identifying m tags per slot and reducing collision probability. Figure 7 [Figure 7: see original paper] shows that for 1000 tags, DFSA, MS-DFSA, PIGDFSA (m=8), and OVSF-DFSA (m=32) require 3140, 1015, 820, and 515 slots respectively, representing reductions of 510%, 97.1%, and 59.2% compared to OVSF-DFSA. The advantage of OVSF-DFSA becomes more pronounced as tag count N increases for fixed m.

[Figure 6: see original paper] [Figure 7: see original paper]

3.2.3 System Identification Rate Simulation Results

System identification rate (or algorithm efficiency) reflects the ratio of successfully identified tags to total system slots per identification round. Experiments vary tag count from 5 to 100 in steps of 5. As shown in Figure 8 [Figure 8: see original paper], when N=100, DFSA, PIGDFSA, and OVSF-DFSA (m=32) achieve identification rates of 0.15, 0.32, and 0.42 respectively, representing performance improvements of 180% and 31.25%. Classic DFSA' s low rate stems from single-tag-per-slot limitation. PIGDFSA with 8 antennas can identify multiple tags in parallel, improving its rate. OVSF-DFSA can theoretically identify up to 32 tags per slot, though with only 100 tags, few are assigned to each slot, limiting the algorithm' s advantage and resulting in modest improvement.

[Figure 8: see original paper]

4 Conclusion

Under the ISO/IEC18000-6 international standard, the proposed CDMA-DFSA algorithm combines OVSF spreading code-based CDMA technology with the DFSA protocol to achieve multi-tag identification within a single slot, transforming tag collisions into code collisions. Simulation results demonstrate that when frame length fs > 2 and OVSF code length m > 2, OVSF-DFSA improves system throughput by m times compared to classic DFSA and outperforms other algorithms in total time slots and identification rate. However, collision slots and idle slots still exist within a reader' s frame. Future work will incorporate adaptive slot allocation principles to skip collision and idle slots, further improving system throughput.

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Note: Figure translations are in progress. See original paper for figures.