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Collision Reduction Schemes Based on Precise-Optimal Frame Length in Slotted Aloha RFID System

Graduate School of Chosun University

Department of Computer Engineering

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Acronyms

ACK	Acknowledgement
CE	Capture Effect
CRC	Cyclic Redundancy Check
DFSA	Dynamic Frame Slotted Aloha
EM	Electromagnetic
EPC	Electronic Product Code
ERP-FSA	Exponential Random Partitioning- Frame Slotted Aloha
FS	Frame Sync
FSA	Frame Slotted Aloha
G-2	Generation 2
ID-FSA	Improvised Dynamic- Frame Slotted Aloha
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
N-ACK	Negative Acknowledgement
PC	Protocol Control
PTSE	Precise Time System Efficiency
QRep	Query Reply
RFID	Radio Frequency Identification System
RN	Random Number
SA	Slotted Aloha
SE	System Efficiency
TSE	Time System Efficiency
UHF	Ultra High Frequency

ABSTRACT

Collision Reduction Schemes Based on Precise-Optimal Frame Length in Slotted Aloha RFID System

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A Radio Frequency Identification (RFID) System is a widely adopted automatic identification technology that has been used in a range of applications including logistics, inventory, retailing, public transportation and security. An RFID system typically consists of a reader and multiple tags in which the reader aims to collect the information from the tags. During the identification process, multiple RFID tags transmit their identification information arbitrarily to the designated reader using a shared wireless channel. If there occur two or more simultaneous transmissions from the tags, the transmitted identification packets are assumed to be collided and cannot be decoded correctly by the reader. Therefore, designing and optimizing Anti-Collision Algorithms (ACAs) are fundamental to the effective use of RFID systems.

An EPC-Global G2 RFID system has adopted a Frame Slotted Aloha (FSA) as its ACA. One of the common approaches, popularly used to maximize the system performance (tag identification efficiency) of FSA based RFID systems, is to find the optimal value for the frame length relative to the contending population size of the RFID tags. Several analytical models that have been developed so far for

finding the optimal frame length are inaccurate because they lack the precise characterization of timing details of the underlying ACA. We investigate this promising direction by precisely characterizing the timing details of the EPC Global G2 protocol and used it to derive the precise-optimal frame length model. The main objective of the model is to suggest the optimal frame length value that maximizes the performance of the RFID system. The derived model is further compared with conventional model to investigate the preciseness of the model and its effect in performance improvement in RFID System. Rigorous numerical analysis shows that the optimal frame length derived from the new extended model is precise, whereas that of from the conventional model deviates significantly from the true optimal value, particularly when the number of tags is high. For typical RFID system, with the use of the optimal frame length value, theoretically, the system efficiency can be maximized up to 83.75 %.

Dynamically adjusting the optimal frame length in accordance with the contending tags is a smart approach to reduce the collision in the system. The optimal frame length can only optimize the system performance if the reader knows the exact number of contending tags. However, in real RFID system the exact number of interrogating tags is always unknown. Therefore, to choose the precise–optimal frame length, the number of tags must be estimated either by using a separate estimator or with the feedback from the reader during the inventory process.

As an effort to maximize the performance of the RFID system, we exploit the potential benefit that can be achieved by using an optimal frame length for an estimated number of tags and proposed two simple collision reduction schemes. The proposed schemes are Improvised Dynamic-Frame Slotted Aloha (ID-FSA) scheme and Exponential Random Partitioning-Frame Slotted Aloha (ERP-FSA) Scheme. The ID-FSA scheme dynamically assigns the next optimal frame length based on estimated number of collided tags in the collision slots from the current frame. On the other hand, an ERP-FSA scheme dynamically adjusts the tag population for the next frame based on the information of collided slots from the current frame. It first determines that, comparing with the frame size, whether the contending tags can be optimally accommodated in the given fixed frame size or not. If the remaining unread tags cannot be maximally accommodated in the given fixed frame size then it divides the contending tag population until the applied frame size becomes optimal.

Comparing with the conventional schemes, the simulation result reveals that our proposed schemes results in 2 – 5% performance improvement. The ERP- FSA algorithm has a performance improvement when the initial frame size is small, however, performs less compared with an ID-FSA algorithm. Furthermore, the ID-FSA scheme has performance superiority in terms of time system efficiency even in the dense tag environment and at various initial frame lengths values. Therefore, it proves that the ERP-FSA scheme has the potential to improve the performance of RFID system in a sparse tag environment where we can adjust smaller frame size. Moreover, the ID-FSA scheme can be adopted in any RFID systems without additional overhead and complexity to improve the performance of the system.

ABSTRACT

슬롯티드 알로하 RFID 시스템에서 최적 프레임 사이즈 기반의 충돌 감소 기법

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무선 주파수 식별 (RFID) 시스템은 물류관리, 물류창고, 소매업, 공용 수송, 보안 등의 다양한 어플리케이션에서 사용되는 자동 식별 기술에 폭넓게 사용되고 있다. RFID 시스템은 주로 리더기와, 리더기가 태그로부터의 정보 수집을 목표로 하는 다수의 태그들로 이루어져 있다. 식별 과정 동안, 다수의 RFID 태그들은 자신의 식별 정보를 공유된 무선 채널을 이용하여 리더기에게 임의적으로 전송한다. 만약 둘 이상의 태그로부터 동시 전송이 일어난다면, 전송된 식별 패킷들은 충돌을 발생시키고, 리더기에 의한 해독이 불가능하다고 가정된다. 그러므로, 충돌방지 알고리즘(ACA)들을 디자인하고 최적화시키는 연구는 RFID 시스템의 효과적인 사용을 위해서 필수적이다.

EPC-Global G2 RFID시스템은 충돌 방지 알고리즘(ACA)으로 프레임 슬롯티드 알로하(FSA) 기법을 사용하여왔다. FSA 기반의 RFID시스템에서 시스템 성능(태그 식별 효율)을 극대화하기 위해서 주로 사용되는 일반적 접근 방법 중의 하나는 RFID 태그의 밀집도 (태그의 수)에 따른 최적의 프레임 길이를 찾는 것이다. 현재까지 연구된 최적 프레임

길이를 찾기 위한 몇몇 분석적인 모델들은 사용되는 ACA 기법의 타이밍 정보에 대한 정확한 특성화가 부족했기 때문에 최적화되어 있다고 보기 어렵다. 본 연구에서는 EPC Global G2 RFID 프로토콜을 토대로 타이밍 정보를 정확하게 정의하고, 이를 기반으로 정확한 최적 프레임 길이를 도출할 수 있는 모델을 제안하였다. 제안된 모델의 주요 목적은 RFID 시스템의 성능을 극대화하는 최적 프레임 길이를 도출하는 것이다. 제안된 모델에 대한 RFID시스템의 성능 향상효과와 모델의 정확성을 검증하기 위해서 이전 모델과 성능 비교를 수행하였다. 엄격한 수리적 분석을 통하여 제안된 모델로부터 유도되는 최적의 프레임 길이가 정확하다는 것을 확인하였으며, 태그의 개수가 많은 경우 기존 모델과 비교하여 실제 최적화 값에 더 근접함을 알 수 있었다. 구체적으로 일반적인 RFID 시스템에 비해 최적 프레임 길이 값을 사용함으로써 이론적으로 83.75%까지 시스템 효율을 개선할 수 있음을 확인하였다.

경쟁 태그의 수에 따라 최적의 프레임 길이를 적응적으로 변화시키는 것은 시스템에서의 충돌 확률을 줄이기 위한 좋은 접근 방법이다. 만약 리더기가 경합 태그의 정확한 수를 알고 있다면 최적의 프레임 길이를 도출하여 시스템 성능을 최적화 할 수 있다. 그러나 실제 RFID 시스템에서 액티브한 태그의 정확한 숫자를 예측하는 것은 불가능하다. 그러므로 정확한 최적 프레임 길이를 선택하기 위해서 태그의 수는 별도의 예측기를 사용하거나 리더기와 태그의 송수신 과정 동안 리더기로부터의 피드백 정보를 사용하여 추정하여야 한다.

RFID 시스템의 성능을 극대화하기위한 노력의 일환으로, 본 연구에서는 태그의 수에 대한 예측으로부터 도출될 수 있는 최적의 프레임 길이를 기반으로 두 가지 충돌 해소 기법을 제안하였다. 제안 된 기법들은 즉흥적 동적 프레임 슬롯티드 알로하 (ID-FSA) 방식과 지수적 랜덤 파티셔닝-프레임 슬롯티드 알로하 (ERP-FSA) 기법이다. ID-FSA 방식은 현재

프레임의 충돌 슬롯 정보로부터 추정된 액티브 태그의 수에 기초하여 적응적으로 다음 프레임 길이를 산출한다. 반면에 ERP-FSA 방식은 현재 프레임으로부터 충돌된 슬롯의 정보에 기초하여 동적으로 다음 프레임에 접속을 시도하는 태그의 수를 전송 확률을 이용하여 제어한다. ERP-FSA 방식에서는 먼저 고정된 프레임 길이에 대해 접속을 시도하는 추정 태그의 수가 적절한지를 평가한다. 만약 남아있는 읽지 않은 태그들이 주어진 고정된 프레임 사이즈에 최대한으로 수용될 수 없다면, 프레임 사이즈가 최적화 될 수 있도록 접속 시도 태그의 수를 확률 값으로 제어한다.

시뮬레이션 결과로부터 기존 방식과 비교하여 본 연구에서 제안된 방식의 결과가 2~5%의 성능 향상이 있음을 확인할 수 있다. ERP-FSA 알고리즘은 초기 프레임 사이즈가 작은 경우 성능 향상이 두드러졌으나, ID-FSA 알고리즘에 비해 성능 향상의 정도가 미미하였다. 뿐만 아니라, ID-FSA 방식은 밀도가 높은 태그 환경에서도 TSE(time system efficiency) 성능이 모든 초기 프레임 길이에 대해 우수함을 보여주었다. 결론적으로 ERP-FSA 방식은 태그의 밀도가 낮은 경우 RFID 시스템의 성능을 향상시킬 수 있는 여지가 있으며, ID-FSA 방식은 추가적인 오버헤드나 복잡도 증가 없이 다양한 RFID 시스템 환경에서 성능을 개선할 수 있음을 확인하였다.

I. Introduction

A. Research Overview

With the remarkable development and rapid growth of wireless technologies Radio Frequency Identification (RFID) Systems is being used more widely nowadays. Logistics, inventory management, retailing, public transportation and security are some of the application domains where RFID system is widely used [1] -[4]. One of the main reasons that drive the growth of an RFID system is its ability to identify objects wirelessly without line of sight.

A simple RFID system consists of an interrogating device called a reader and multiple tags. The reader is more powerful device with its sufficient memory and computational resources, however, the tags vary in terms of their computational capability and power resources. They range from passive tags, which respond only with at the reader's command, to semi-passive tags and active tags, which have their own on-board power supply [5]. Further active tags are privileged with other resources such as memory, transceiver and microcontrollers. Despite of low computational capability, passive tags are popularly used due to their low cost [6], on the other hand, active tags are confined within certain special purpose applications as they are more expensive compared with other tags.

The reader transmits an RF signal during the identification process, which on received by the tag send back the response. The multiple RFID tags transmit their identification information arbitrarily to the designated reader using a shared wireless channel. If more than one tag transmits simultaneously, the transmitted identification packets are assumed to be collided and cannot be decoded correctly by the reader. It results in wastage of bandwidth, energy and increases identification delays. Therefore, designing and optimizing Collision Reduction Protocols (Anti-Collision Algorithms) are fundamental to the effective use of RFID systems.

B. Motivations

In the literatures there have been adequate discussions on the issue of Anti-Collision Algorithms. One of the responsible bodies for RFID air interface standards is an EPC- Global, which develops the industry-driven standards for international supply chain networks, have adopted a simply designed Frame Slotted Aloha (FSA) [7] as its ACA in its latest amendment (EPC Global G2 [8]). In FSA algorithm, the available channel is divided into time slots (Slotted Aloha) and further the time slots are organized into frames. In each frame, which has a number of slots, the tags can respond to the reader's command only once and each time slot is long enough for the tags transmit data. Hence, each unidentified tag randomly selects one time slot in a frame and sends its data and it will try again in the next frame unless it gets identified. Therefore, the performance of the FSA depends upon the suitable frame size.

Since the performance of the FSA depends on the frame size, many of the literatures proposed a modification of FSA mechanism known as Dynamic Frame Slotted Aloha (DFSA) algorithm [7][12]. The DFSA algorithm dynamically adjusts the frame size with the contending tag population by estimating the number of contending tags from previous frame. In particular, adjusting the frame size with a contending tag population is an effective technique to improve the system performance but this is not the optimal solution that can optimize the system performance. Hence, to achieve optimum system performance the frame length should not only be dynamically adjusted but also to be optimally regulated corresponding with the tag population.

Many literatures tried to find the optimal frame length relative to the contending tag population and assumed that all the time slots are equal and concluded that the highest time system efficiency can be achieved when the number of slots in a frame is equal to the contending tag populations. However, EPC Global G2 clearly classifies the slots in a frame into success, collision and idle slots. Comprising this information, some of the literatures [9] [10] tried to present an analytical model for the frame length which is optimal for the given number of tags. Still, these conventional analytical models have some limitations; either they lack precise characterization of timing details of underlying ACA or don't consider the physical layer capture effect.

C. Thesis Contribution

In this thesis, first, an analytical model for optimal frame length has been developed. The presented analytical model not only precisely characterizes the timing details of each slot in accordance with the EPC Global G2 specifications, but also considers the physical layer capture effect. Through rigorous numerical analysis we analyze the effectiveness of the proposed analytical model in the system performance.

Furthermore, with reference to the precise optimal frame length, two collision reduction protocols were developed that can utilize the optimal frame length for estimated number of tags and optimize the system performance nearly close to the theoretical upper bound.

First, an Improvised Dynamic–Frame Slotted Aloha (ID-FSA) algorithm has been proposed which optimally assigns the next optimal frame length based on the estimated number of tags in the collided slots from the current frame. This method suggests that to achieve the optimum system performance the frame length should not only be dynamically adjusted but also to be optimally regulated corresponding with the tag population. Second, Exponential Random Partitioning–Frame Slotted Aloha (ERP-FSA) algorithm has been proposed. The ERP-FSA algorithm first determines that, compared with the frame size, whether the unread tags can be optimally accommodated in the given fixed frame size or not. If the remaining unread tags cannot be optimally accommodated in the given fixed frame size then it divides the contending tag population until the applied frame size becomes optimal.

With rigorous performance evaluation carried using the custom simulator developed in Matlab; we demonstrate that the ERP-FSA algorithm is suitable only under certain circumstances where the system uses the small frame for a small number of tags. On the other hand, the ID-FSA algorithm, which is more suitable for handling any number of contending tag population, has significant performance improvement in terms of efficiency of the system.

D. Thesis Organization

We first present an introduction to the RFID systems with focus on RFID Anti-Collision Algorithms. Further, we discussed about the essential details of the EPC Global G2 protocol comprehensively with some dynamic frame adjustment techniques in chapter II. The analytical models along with our proposed precise model to estimate the optimal frame length is introduced in chapter III. The study and derivation of analytical models are followed by the comparison of conventional and proposed models with respect to major characteristics and achievable performance. These results give the basic guidance in designing optimal collision reduction protocols for various potential network environments. Chapter IV contains the proposed collision reduction protocols and performance of these protocols has been evaluated in chapter V. Finally, chapter VI concludes the thesis.

II. Preliminaries

This chapter provides a brief introduction of RFID technology with an overview of existing standards and described the main concept of the standard focusing on its anti-collision algorithm.

A. RFID System

Typically, an RFID system consists of reader and tags. A tag consists of an electronic microchip and coupling elements. These tags are attached to the objects intended for the identification. On the basis of computational capacity and power supply, the tags are classified into three types: Passive, semi-passive and active tags. Passive tags have no power and limited computational capacity such as no ability to sense channel, detect collision and communicate with each other. Semi-Passive Tags are similar to passive tags having the advantage of on board power chip to energize the microchip, however, passive tags have to use the sensed energy source from the reader. The active tags have their own energy source and are privileged with the computational capacity such as they can sense the channel, detect collisions and communicate with each other. Despite of its computational capacity the passive tag is popularly used in major application domains due to its low cost, however, the active and semi-passive tags are special purpose tags and are expensive.

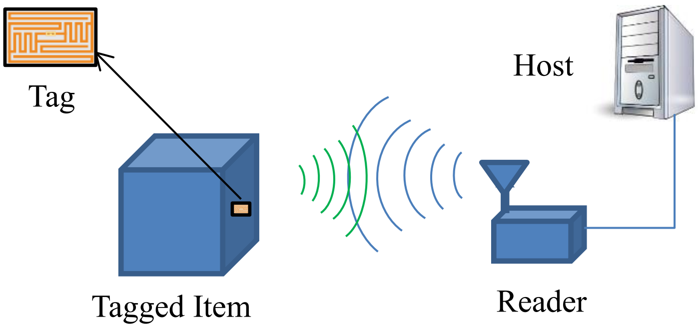


Figure 2-1: RFID System

The reader, or interrogator, is a device which can read the data from the tags. The reader broadcast the interrogation information through the Electromagnetic (EM) Waves and passive tags collects enough energy to be energized and backscatters the signals with their information. Figure 2-1, shows the basic components of RFID system where the tag is attached to the item and reader interrogates the item's information. The interrogated information is further delivered to the host for further processing. During the interrogation process if two or more tags send their information concurrently then the reader cannot perceive them and treat them as collided information. So the collided tags should resend their information. To prevent more collisions, an anti-collision algorithm has been used in the MAC layer of RFID system.

B. Anti-Collision Algorithms

The Anti-Collision Algorithms are vital for the performance of the RFID system. Without the Anti-Collision Algorithms the replies from the tags in the reader would collide and thereby prolong their identification process. Similarly, the collision causes the waste of bandwidth and energy. Broadly, there are two categories of Anti-Collision Algorithms in RFID System [13].

1. Deterministic Anti-Collision Algorithms

In deterministic anti-collision algorithms, first of all, the reader splits the given tag population and identifies a set of tags that respond in a given time. The tree based protocols [14]-[18] are categorized under this Deterministic Anti-Collision Algorithms.

The tree based protocols are able to single out and read every tag, provided that contending tags are splited until it reaches to the single tag node. Splitting is based on the contention information obtained from the previous cycle. The contending tags are splited either by the tags' serial number or by generating the random numbers to be used for splitting the tree branches. In tree based anti-collision algorithms the tags are interrogated using an interrogation cycle which determines whether the contending tags are more than one or not. The objective of these interrogation cycles is to split tags into a manageable set of tags or particularly single tag.

The performance of the tree based protocols is efficient when the number of tags in the system is small. However, with the increase in the number of contending tags the splitting mechanism takes longer time thereby decreasing the efficiency of the system.

2. Probabilistic Anti-Collision Algorithms

The Aloha based algorithms lies under the probabilistic anti-collision algorithms, in which the time is divided into time-slots, as in slotted aloha, and the tags are allowed to send their information at the beginning of each slot. When the tag has to send the data it waits for a finite number of slots to send its data. If no other tags have chosen the same slot for transmission then the information of that tag is transmitted successfully otherwise the collision occurs and the information has to be retransmitted again waiting for the finite time slots. In Slotted Aloha, the collided tag frequently tries to access the channel obstructing other tags which are potentially valid in a particular slot. Therefore, to reduce the frequent collision from collided slots, Frame Slotted Aloha (FSA) algorithm is designed such that each tag can transmit only once in one frame. The reader synchronizes the whole interrogation process as the tag has to send its data within the definite time slot. The frame size may be adjusted based on the information collected from the previous frame which gives information about the number of collision, idle and successful slots. The frame adjusting capability is advantageous according to the tag population which may help in reducing the unwanted idle and collision slots. The probabilistic approach is faster in comparison to the deterministic approach because of its low overhead. However, it may suffer from the tag starvation problem.

In probabilistic anti-collision algorithm, when the contending tag population is low the probability of the collision is also low so that the identification duration is also short. On the other hand, if the tag population increases, collision probability also increases so that the identification duration rapidly increases. Therefore, the performance of the probabilistic algorithms highly depends upon the population of tags. If the frame slotted aloha (FSA) algorithm is used then the collision ratio is highly reduced. The variations of FSA algorithm have been proposed in many literatures [9] [12] [21]. Among Aloha based algorithms, FSA algorithm is preferred to be used in RFID system due to its simplicity and efficiency. Hence, the

EPC Global has also adopted FSA as its Anti-Collision Algorithm in its latest amendment of Generation 2 (G2) protocol i.e., EPC-Global G2 protocol.

C. EPC Global G2 Protocol

EPC Global is one of the responsible bodies for RFID air interface standards, which develops the industry-driven standards for international supply chain networks. Its latest amendment in EPC Gen 2 class 1 UHF standard has been approved by the International Standards Organization (ISO) to be published as an ISO 18000-6C standard. Both standard details the parameters for how the reader send and receive data from the tags. It also specifies the frequencies and channel to be used, as well as bandwidth, frequency hopping and other technical details.

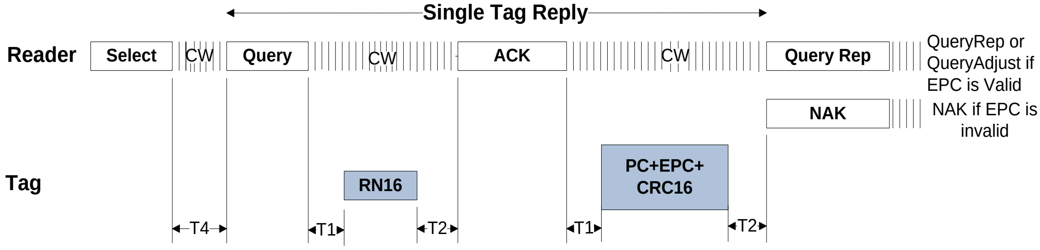
This section provides the essential details specified in the RFID EPC Global G2 standard which uses the Frame Slotted Aloha algorithm for medium access mechanism. Further, we precisely characterize the variable length slots.

1. Frame Slotted Aloha in EPC Global

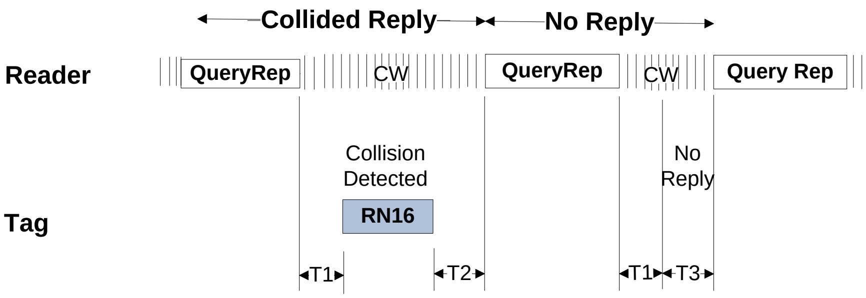
The EPC-Global G2 protocol adopts the well-known frame slotted aloha as its ACA. The fundamental principle of this popular protocol is that the fixed time frame determined and broadcasted by the reader is slotted into numerous discrete time intervals (slots) and each tag randomly selects any one slot to transmit its identification information. Therefore, independent transmission events from the tags can result in any of the following:

1. Idle (None of the tags transmit)
2. Success (Single tag transmits in a slot)

3. Collision (Two or more tags transmit in the same slot).



(a) Single Tag Reply (Success Slot)



(b) Collided and No Tag Reply (Collided and Idle Slots)

Figure 2-2: Success, Collision and Idle tag reply in EPC Global G2

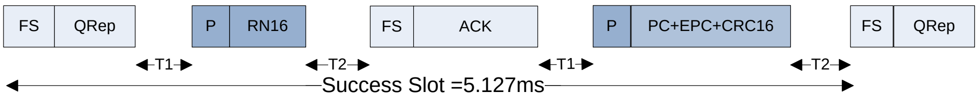
Fig. 2-2 (a) shows the process during successful identification. The reader begins with the tag selection by transmitting the select command. The select command activates the tags and requests them to participate in the identification process. After the tags are activated, the reader sends the query command. The query command begins a new frame and requests each tag to generate a 16 bit random number (RN16) to select their transmitting slot. The tags maintain their slot counter according to the selected value. Tags decrease their slot counter at the end of each slot. As soon as the slot counter is zero, the tags reply with RN16. On the successful reception of RN16, the reader sends the Acknowledgement (ACK). The ACK command requests a tag to send its EPC. As a response, the tag sends its EPC along with other control messages, such as Protocol Control (PC) and 16 bit Cyclic Redundancy Check code (CRC16). If there is no error and the EPC code is valid then the reader begins the next slot by sending a Query Reply (QRep). In the case of error in EPC, the reader sends a Negative-ACK (NAK) command. The NAK requests the tag involved to transmit in the next frame.

Fig. 2-2 (b) shows the process during the collision and idle states. In the case of collision, the reader attempts to resolve the collision or without resolving the collision, it may send the NAK or QueryRep command. Similarly, if no tags reply for some threshold time, which is represented as T3 in Fig. 1 (b), the reader assumes it to be idle slot and begins the next slot by issuing a new QueryRep command.

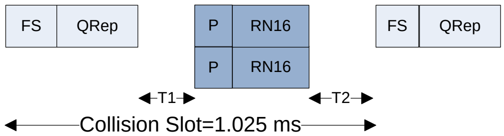
2. Timing Details in EPC Global

Table 2-1: Timing Parameters used to calculate the time duration of each slot

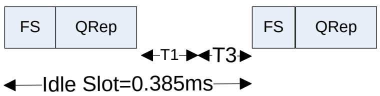
Parameters Name	Symbol	Parameters Name	Symbol
QRep	4 bits	EPC	96 bits
ACK	18 bits	FS (Frame Sync)	100 μs
CRC16	16 bits	T1	125 μs
RN16	16 bits	T2	62.5 μs
PC	16 bits	T3	62.5 μs
P (preamble)	6 bits	Data Rate	40 kbps



(a) Success Slot Duration



(b) Collision Slot Duration



(c) Idle Slot Duration

Figure 2-3. Success, Collision and Idle slot duration in EPC Global G2

In the EPC-Global G2 protocol, each command, data symbol, preamble and turnaround transmission period between the reader and tag are comprised of certain time duration, as shown in Fig. 2-2 (a) and (b). T1 and T2 are the turnaround time. T1 is the time interval from a reader's transmission to the tag's response, whereas T2 is the time interval from the tag's response to the reader's next transmission. T3 is the idle time interval, as mentioned above. T4 is the time between the select command and the first query command. From the parameters presented in Table 2-1 and the timing diagrams in Fig. 2-3 (a), (b) and (c), the slot time duration for success, collision and idle events can be calculated as follows:

$$T_S = T_{QREP} + 2T_1 + T_{RN16} + 2T_2 + T_{ACK} + T_{(PC+EPC+CRC)} = 5.127ms \quad (1)$$

$$T_C = T_{QREP} + T_1 + T_{RN16} + T_2 = 1.025ms \quad (2)$$

$$T_I = T_{QREP} + T_1 + T_3 = 0.385ms \quad (3)$$

3. Slot Distribution in EPC Global

In EPC-Global G2, each tag can access the channel only once in a single frame. The collided tags need to wait for another frame to transmit again. In any arbitrary frame, if the frame size of N slots is used for n number of tags, then r number of tags in one slot is distributed binomially with the parameters n and 1/N [9]:

$$B_{n,1/N}(r) = \binom{n}{r}(1/N)^r(1-1/N)^{n-r}. \quad (4)$$

The *r* number of tags in a particular slot is called the occupancy number of a slot. Therefore, the expected number of slots with occupancy *r* is given by the following equation:

$$a_r^{N,n} = NB_{n,1/N}(r) = N\binom{n}{r}(1/N)^r(1-1/N)^{n-r}. \quad (5)$$

When *r = 1*, the particular slot is filled with precisely one tag. Therefore, the number of successful slots (*S*) out of N slots in a frame is given by

$$S = a_1^{N,n} = NB_{n,1/N}(1) = n(1-1/N)^{n-1}. \quad (6)$$

From (5), the number of idle slots (*I*) can also be expressed as

$$I = a_0^{N,n} = NB_{n,1/N}(0) = N(1-1/N)^n. \quad (7)$$

From (5), (6) and (7), the number of collision slots (*C*) can be written as

$$C = a_{\geq 2}^{N,n} = N - S - I. \tag{8}$$

4. Slot-Count Q Selection Algorithm in EPC Global

In EPC Global G2 for the performance optimization of the system, Q selection algorithm has been used. To select the optimal Q, the information about the number of interrogating tags (n) must be known in advance. However, in practical scenario the exact number of tags has been always unknown. So Q selection Algorithm uses the information such as, number of success, collision, and idle slots, from the previous frame and makes changes in the next frame size so that the system can be optimized.

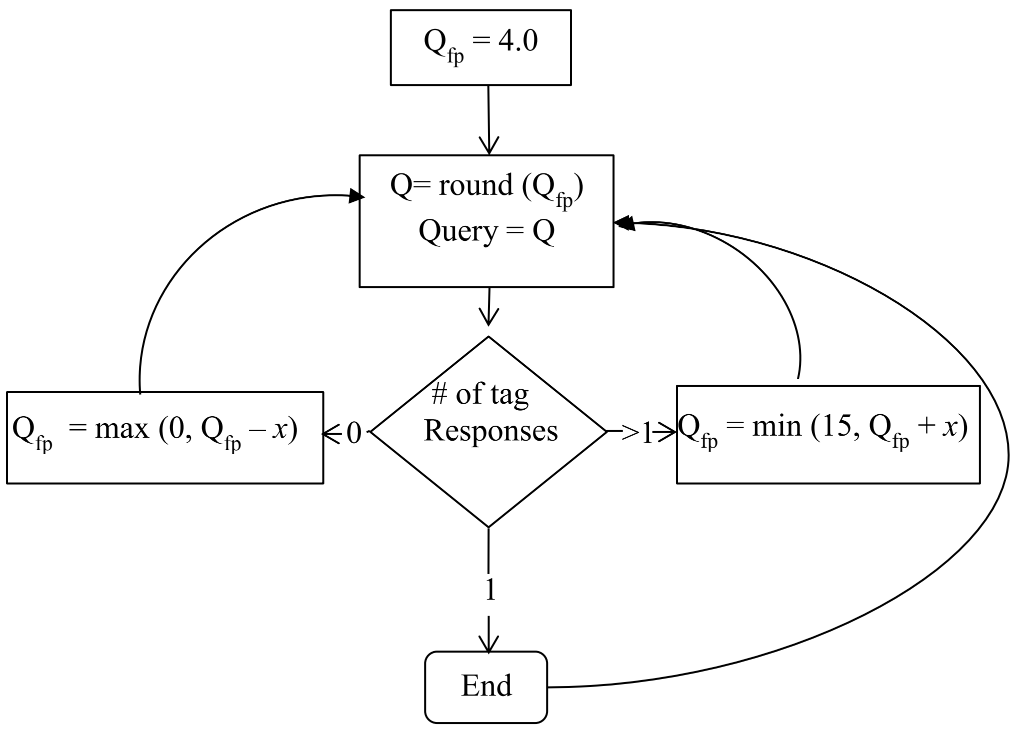


Figure 2-4: Slot count Q selection Algorithm

As shown in Fig 2-4, this is an example of slot count Q selection algorithm given in Annex D of [8]. The Q_{fp} is the parameter that is adjusted slot by slot according to the status of the received slot. Q is an integer value (rounded Q_{fp}) which ranges from 0 - 15. Every tag receives a query command from the reader having a frame size $N = 2^Q$ and every tag randomly generates a slot counter between 0 to N-1. Following the example, Q_{fp} is increased by *x* when collision slot is detected and decreased by *x* when idle slot is detected otherwise for the success slot there is no change in Q_{fp}. So for the next frame the frame size will be $N = 2^{round\ (Qfp)}$. The typical values for *x* suggested in the protocol are in the range of (0.1, 0.5). However the slot count Q algorithm only performs well if floating value is optimally chosen. According to [8] a reader should use small values of *x* when Q is large and larger values of *x* when Q is small. Moreover, the selection of the initial Q for the first frame has always become a difficult task without a priori knowledge of network size and if the network size is large then the Q adjustment strategy fails and the performance of the system heavily degrades.

D. Dynamic Frame Size Adjustment Schemes

The performance of the RFID anti-collision algorithm based on FSA depends on a frame size updating approach. A variety of such approaches have been proposed to enhance the performance of the RFID system. The achievable performance of those schemes depends upon the frame size updating strategy that adjusts the number of slots in a frame with the estimated number of tags. Since the true number of interrogating tags is always unknown, the frame size updating schemes needs to estimate the number of tags and broadcast the corresponding frame size. The FSA algorithm in which the reader shows the ability to adjust the next frame length dynamically according to the current frame statistics is also known as Dynamic

Frame Slotted Aloha (DFSA) Algorithm. Some of the DFSA schemes that have been proposed to enhance the system performance are discussed in this subsection.

1. Bayesian Slot-by-Slot Updating Scheme

Floerkeimer in [19] presented a transmission control strategy that evaluates the current frame size as the frame progresses. The individual steps of the broadcast scheme are adapted from [20] to suit the nature of frame slotted aloha in RFID:

1. Compute the frame size based on the current probability distribution of the random variable n that represents the number of tags transmitting.
2. Start Frame with N slots and wait for tag replies
3. Update probability distribution n based on evidence from the reader at the end of the frame. The evidence comprises the number of empty, success and collision slots in the last frame
4. Adjust probability distribution n by considering newly arriving tags and departing tags including the ones which successfully replied and do not transmit in subsequent slot

Based on the empirical results a normalized x is chosen as $x = 0.8/Q$. It has claimed that the performance of the Q algorithm is poor by updating the Q value with constant $x = 0.8/Q$. However, the performance of the Q slot count algorithm can be significantly increased when the changes to Q are restricted to the incremental changes. Under these conditions the oscillations of the slot count Q algorithm are damped and the simulated throughput is similar to the other frame based transmission schemes. In this thesis, for the comparison with our schemes we have chosen the normalized x as $x = 0.8/Q$ and updates the Q value at the end of the slot.

2. Schoute Frame size updating scheme

In [21], Schoute et. al. proposed an estimation technique that gives the expected number of contending tags that still remain to transmit their information after a frame has been executed. This backlog estimation technique for DFSA algorithm is exact under the assumption that the frame size is chosen in such a way that the number of users that transmit in each time slot is Poisson distributed with mean 1. The total number of tags that have not been read, represented as backlog B_t, after the current frame is then simply given by [24]

$$C_{tags} = Lim_{n\to\infty} \frac{1-P_s}{P_c} = 2.3922 \qquad (9)$$

Where, Ps and Pc denote the success and Collision Probability. Hence the estimated number of tags will be:

$$B_t = 2.39 \times C \qquad (10)$$

Where, C is the number of collided slots in a frame.

Note that FSA algorithm assisted temporal collision reduction process slows down as the number of contending tags increases. Hence to accelerate the reduction process, schemes like [9] [19] and [21] have been proposed. The above dynamic frame size adjustment schemes depend upon the estimated number of tags. Using the estimated value of contending tags and dynamically adjusting the frame size is a smart approach to reduce the collision in the network. However, the calculated so-called frame size based on the non-precise estimation, in reality, would not be optimal. Hence, to achieve the optimum system performance the frame length should not only be dynamically adjusted but also to be optimally regulated corresponding with the tag population.

III. Analytical Models to Estimate Optimal Frame Length

Although, many literatures effort in improving the performance of RFID systems by adjusting the frame size in accordance with the estimated number of tags they ignored to utilize the optimal frame length. In this section we introduce a precise optimal frame size for FSA anti-collision algorithm in an RFID system. We claim the preciseness of this model, as we have considered the precisely characterized time duration of slots introduced in chapter 2 and physical layer capture effect phenomenon.

A. Conventional Model

This subsection presents two conventional performance evaluation metrics, named System Efficiency (SE) and Time System Efficiency (TSE). In addition, how these metrics are used to derive the optimal frame size is also reviewed.

1. System Efficiency

Metric SE simply considers the number of successful slots out of the total number of slots, as given in the following equation [9]

$$SE = \frac{S}{N} = \frac{S}{I+S+C}. \tag{11}$$

From (6) and (11)

$$SE = \frac{n\left(1-1/N\right)^{n-1}}{N}. \tag{12}$$

The optimal N (i.e. N*) that maximizes SE can be calculated easily by solving the following differential equation:

$$\frac{d\left(SE\right)}{dN} = 0. \tag{13}$$

Solving (13) gives

$$N^{*} = n. \tag{14}$$

Equation (14) indicates that SE is maximized when the frame size is selected to be equal to the tag population.

2. Time System Efficiency

The SE calculated in the above subsection is not precisely correct because it assumes that the duration for successful, collision and idle events are equal. Nevertheless, as described in the previous section, those event durations are not equal. Porta et. al. in [10] differentiated the duration of idle and successful or collision events and reported that information while calculating SE, which resulted in a new metric called the Time System Efficiency (TSE). In the TSE, the idle slot duration is multiplied by a factor β (which value is T_I/T_S), as expressed in the following equation:

$$TSE = \frac{S}{\beta I + S + C}. \tag{15}$$

The optimal frame size (N*) can be calculated by solving the following differential equation:

$$\frac{d\left(TSE\right)}{dN}=0. \tag{16}$$

The maximum value is achieved when

$$\left(\beta-1\right)\left(1-1/N\right)^{n}+n(1-\frac{1}{N})+(1-n)=0. \tag{17}$$

Solving (17) and finding the roots of N for different sets of tags, the optimal frame size N* for n number of tags can be expressed as

$$N^{*}=4.406\times n-1. \tag{18}$$

Equation (18) suggests that TSE is maximized when the frame size is selected to be 4.4 times larger than the tag population.

B. Precise Optimal Frame Size calculation

Although TSE considers different successful/collision and idle slot event durations, it does not differentiate the duration of the successful and collision events. For EPC Global G2, however, those durations are different, as can be noted in (1) and (2). Therefore, the TSE in (15) has been revised to formulate a Precise TSE (*PTSE*) as follows:

$$PTSE=\frac{S}{\beta I+S+\alpha C}, \tag{19}$$

where α is a multiplication factor (T_C/T_S).

Reconfiguring (19) as

$$PTSE = \frac{S}{I(\beta-\alpha)+S(1-\alpha)+\alpha N}. \tag{20}$$

Substituting the values of S and I from (6) and (7) in (20) gives

$$PTSE = \frac{n(1-1/N)^{n-1}}{N(1-1/N)^{n}(\beta-\alpha)+n(1-1/N)^{n-1}(1-\alpha)+\alpha N}. \tag{21}$$

The optimal frame size (N*) can be then obtained by differentiating *PTSE* with respect to N as follows:

$$\frac{d(PTSE)}{dN} = 0. \tag{22}$$

Upon simplifying (22), the maximum *PTSE* can be achieved when

$$\frac{(\beta-\alpha)}{\alpha}\left(1-\frac{1}{N}\right)^{n} + n\alpha(1-\frac{1}{N}) + \alpha(1-n) = 0. \tag{23}$$

Solving (23) and finding the roots of N for different set of tags, the relation between N* and the number of tags n, can be obtained as follows:

$$N^{*} = 1.46 \times n - 1. \tag{24}$$

All the calculations presented thus far is based on the assumption that the simultaneous transmission of RFID tag information from more than two tags results in a collision. On the other hand, this assumption is not always true because even in the case of simultaneous transmissions, a transmission may be decoded well at the reader if its signal strength is above a given threshold (known as the capture threshold). Such a phenomenon is known as the capture effect (CE).

To consider the CE in *PTSE,* the *PTSE* in (19) is revised as

$$PTSE_{CE} = \frac{S + \gamma(\alpha C)}{I(\beta - \alpha) + S(1-\alpha) + \alpha N}. \quad (25)$$

Note that the mean capture probability (γ) in (25) can be calculated using the following expression [22-23]:

$$\gamma = \sum_{i=2}^{n} p_{cap}(i)\, p_{col}(i), \quad (26)$$

where $P_{cap}(i)$ is the capture probability for *i* collided tags and $P_{col}(i)$ is the probability of *i* tags colliding in a given slot.
Therefore, the optimal frame size can be calculated by differentiating $PTSE_{CE}$ with respect to N, as shown below:

$$\frac{d(PTSE_{CE})}{dN} = 0. \quad (27)$$

Solving (27), the maximum $PTSE_{CE}$ can be achieved when the following equation holds:

$$(1-\frac{1}{N})[(\beta-\alpha)+\gamma\alpha(1-\beta)]+[\gamma\alpha\beta+n\alpha(1-\gamma)](1-\frac{1}{N})+\alpha(1-\gamma)(1-n)=0. \quad (28)$$

Using the values of α = 0.2 and β = 0.075 and solving (28), different optimal frame sizes can be obtained for different capture probabilities (γ), $\gamma \in [0,1]$.

Table 3-1: Optimal Frame Size with Different Capture Probabilities

Average Capture Probability (γ)	Optimal Frame Size (N *)	Precise Time System Efficiency (PTSE)
0	1.459n	0.8375
0.1	1.387n	0.8432
0.2	1.312n	0.8513
0.3	1.231n	0.8599
0.4	1.146n	0.8694
0.5	1.053n	0.8798
0.6	0.951n	0.8916
0.7	0.835n	0.9052
0.8	0.696n	0.9219
0.9	0.509n	0.9449
1	1	1

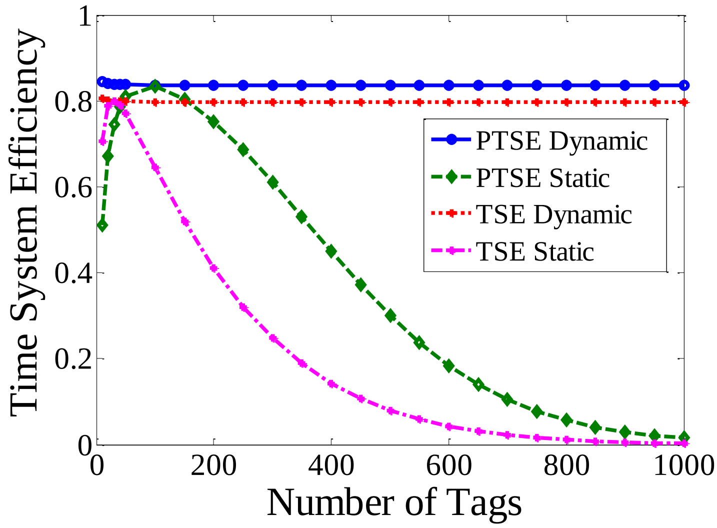
As evident from Eq. (24), the maximum time system efficiency of an RFID system (without considering CE) can be achieved by fixing the frame length to almost 1.46 times larger than the contention population size. On the other hand, this calculation does not hold when the capture probability increases. Table 3-1 shows how the capture probability plays an important role in the optimal frame size estimation and how this optimal frame size calculation is an important feature that should be considered to obtain the optimal time system efficiency.

Note that when $\gamma = 1$, which corresponds to the case of perfect capture (i.e., One tag is always captured regardless of the number of tags involved in the collision), the optimal frame size is 1 and theoretically system efficiency is 100%.

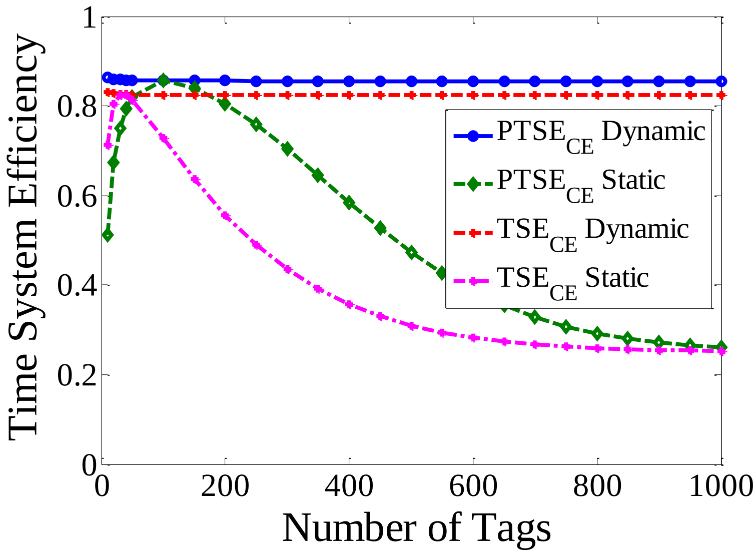
C. Comparison of the Models

This section presents the results obtained from the proposed analytical model and explains how the results of the optimal frame size calculation are more precise than that of the conventional model.

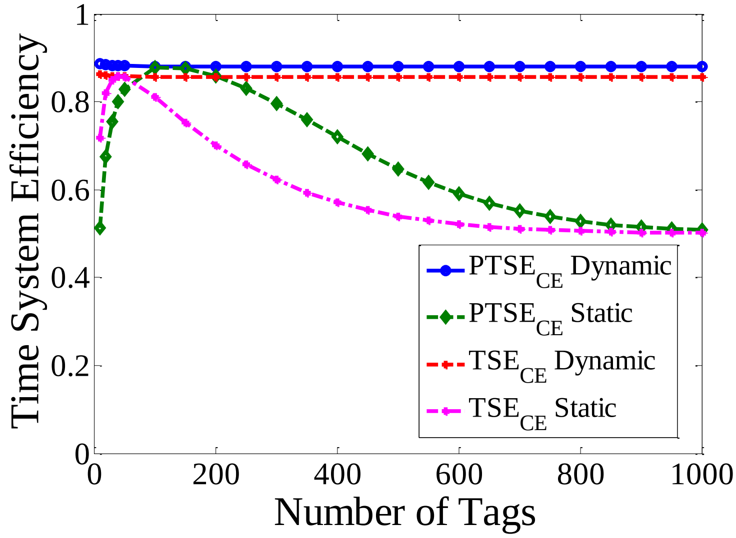
To compare the proposed analytical model with the conventional model, two different schemes used in FSA's were considered: static and dynamic. In the static FSA, the reader broadcasts the frame length once and all the tags use the same frame length throughout. On the other hand, in the dynamic FSA, the reader periodically estimates the tag population, calculates the optimal frame size and broadcasts the calculated frame size. For the static scheme, the frame size consisting of 128 contention slots is considered, whereas for the dynamic one, the frame size (relative to tag population) derived from the proposed analytical model and conventional model are taken into account.



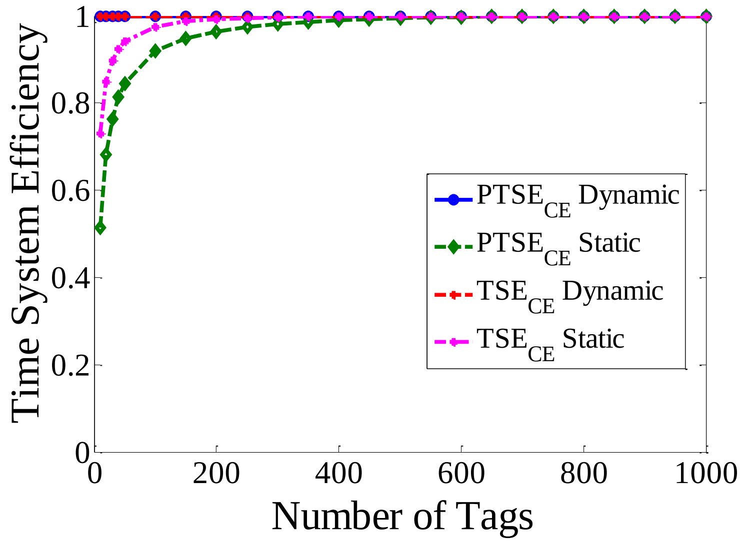
(a) γ = 0 (Without Capture Effect)



(b) γ = 0.25



(c) $\gamma = 0.5$



(d) $\gamma = 1$

Figure 3-1: Comparison of the Time System Efficiency of the Static and Dynamic FSA in RFID Systems

Fig. 3-1 (a) shows the time system efficiency of a static FSA and dynamic FSA calculated using the proposed model and the conventional model for the increasing number of interrogating tags. From the figure, it is evident that the conventional model over-estimates the time system efficiency of the static FSA-based RFID system when the tag population is low (< half the frame size) and underestimates the time system efficiency when the tag population is high. From the same figure, it is also evident that the conventional model underestimates (~ 4%) the time system efficiency of dynamic FSA based RFID systems.

Note that results presented in Fig. 3-1 (a) are for an ideal case, considering the no capture effect, i.e. capture probability $\gamma = 0$. In practical RFID systems, there is a certain capture probability less than one. Fig. 3-1 (b) and Fig. 3-1 (c) shows that when the capture probability increases, the estimation error of the conventional model begins to decrease because the number of collisions in the system is reduced due to capture effects. Therefore, the effect of an incorrect characterization of collision slots cannot magnify the results significantly. When the capture effect is 1 (the hypothetical case in Fig. 3-1 (d)), the time system efficiency estimated using the proposed model and conventional model is the same (100%) for the dynamic because no collisions exist in the system.

The optimal frame size used in conventional FSA based anti-collision algorithm has deviated far from being optimal in both static and dynamic frame sizes. Therefore, to maximize the system performance the proposed optimal value has to be implemented in an RFID system.

IV. Proposed Collision Reduction Protocols

In section 3 we evaluate that the well-chosen frame-size is vital for the performance improvement in FSA algorithm. The performance of the system depends upon the number of allocated slots in the frame. If the less number of slots are assigned in comparison to the number of tags, the performance of the system reduces due to rise in the probability of collision. Likewise, if a high number of slots are assigned, the system efficiency again reduces due to the probability of high number of slots remaining idle. The theoretical optimal frame size has been precisely calculated which has the optimal performance in the RFID system.

Dynamically adjusting the optimal frame size in accordance with the contending users is a smart approach to reduce the collision in the network. This optimal frame size can only be chosen if the reader knows the exact number of contending tags however, in real RFID system the exact number of interrogating tags is always unknown. Therefore, to choose the optimal frame size, the number of tags must be either estimated with separate estimator before the actual inventory, or it is estimated with the feedback from the reader during the inventory process.

Some of the literatures [19] [21] effort to estimate the population size and the estimation technique is based on the feedback during the inventory process. However, their estimation is not exact and it is always a difficult task to precisely estimate the contending tags. Therefore, the adapted so-called dynamic frame size based on the non-precise estimation, in reality, would not be optimal. Hence, the DFSA algorithms have some limitations.

Till date, no attention has been paid to exploit potential benefits that can be achieved by using optimal frame size for the estimated number of tags. As an effort to optimize the performance of the RFID system, we propose two new methods in which the parameter precise-optimal frame length jointly with the popular tag estimation technique [21] has been adopted. Unlike previous models in which the frame length equal to the estimated tag population is regulated, we implemented the optimal frame length for the estimated number of tags or vice-versa.

A. Improvised Dynamic- Frame Slotted Aloha (ID-FSA) Algorithm

Dynamic frame size regulation depends upon the current frame statistics, which gives the number of success, Collision and Idle slot. Some of the literatures followed Schoute [21] which estimates the number of unidentified tags by counting the number of collided slots. According to Schoute each collided slot has 2.39 times the number of tags. Adjusting the frame size with the estimated number of tags can achieve some performance improvement in an RFID system. However, as discussed above the given frame size is not optimal and the achieved performance improvement is only sub-optimal. Therefore, to optimize the performance of RFID system the optimal frame size should be used.

Assuming that there are n interrogating tags in the reader's interrogation zone and the frame size is N time slots. Applying the first frame to interrogate the n number of tags, we can accurately obtain the number of success (S), Collision (C) and Idle (I) slots.

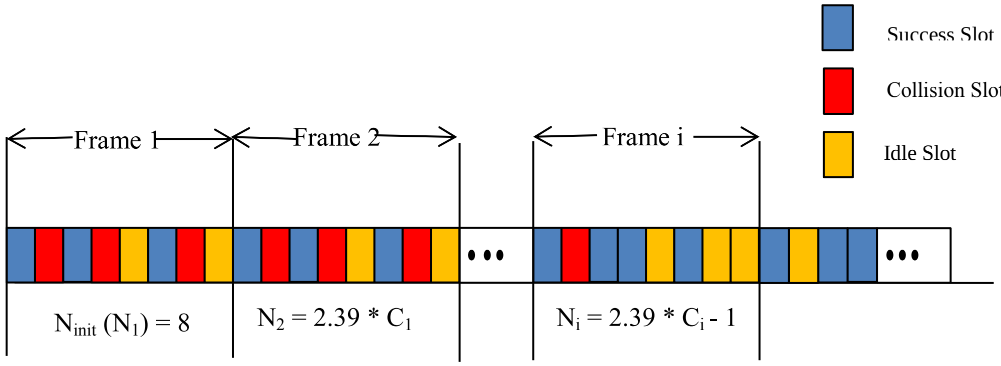


Figure 4-1: DFSA Algorithm Prototype

As shown in the fig 4-1, N = 8 and when n number of tags have been interrogated, the statistics obtained from first frame is C = 3, S = 3 and I = 2. From this statistics or from the observed collided slots what we can estimate is the minimum number of unidentified tags. If C = 3, then from schoute, minimum number of unidentified tags = $2.39 \times C \approx 7$. So, the next frame should be of minimum 7 slots. However, applying 7 slots frame for estimated 7 tags would be suboptimal as verified in the section 3. Therefore, to obtain the optimal time system efficiency, the next frame should be of 1.46 times the estimated number of tags as achieved in our proposed technique in chapter 3.

In Improvised Dynamic Frame slotted Aloha (ID-FSA), we combined the schoute tag estimation approach and our precise optimal frame size allocation approach. First, we estimate the number of unread tags with the schoute collision slots estimation approach and apply our optimal frame size for the estimated unread tags. Schoute et. al. proved that in every collided slot there are 2.39 times the estimated number of collided tags $E(n_c)$ i.e., $E(n_c) = 2.39 \times C$.

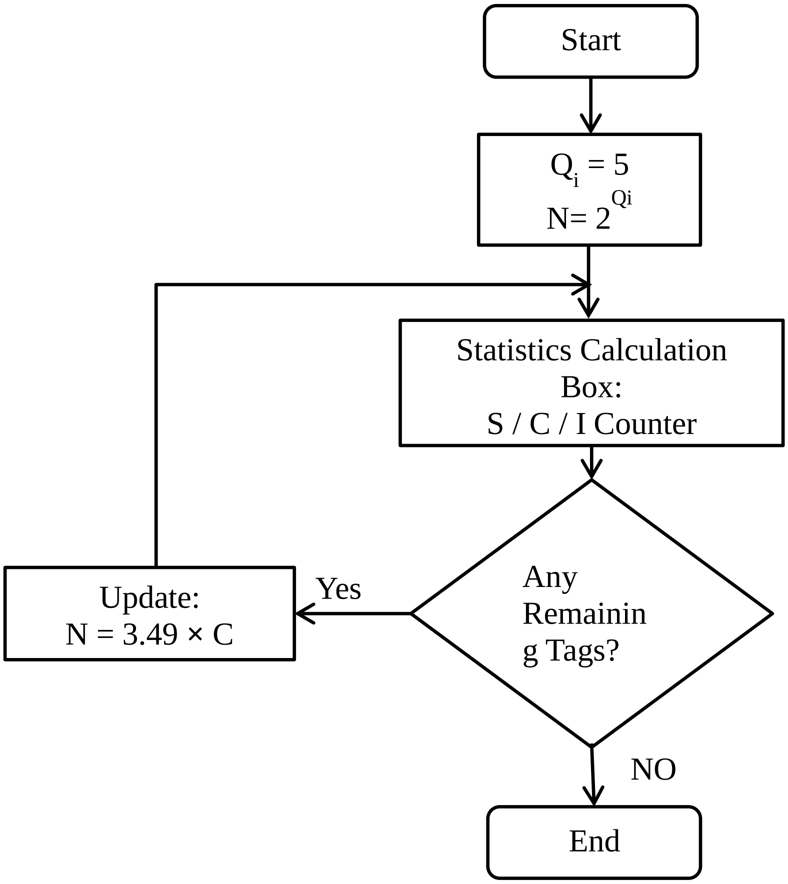


Figure 4-2: ID-FSA Algorithm

Similarly, from our proposed analytical equation for the optimal frame length the optimal N required for n number of tags is N = 1.46 × n. If the estimated number of unread tags from collided slot is E (n_c) = n, then the system will be optimized only if we implement the frame size of N = 1.46 × E (n_c) i.e., N = 3.49 × C.

Using this optimal frame length approach, the ID-FSA algorithm in Fig. 4-2 shows the procedure of dynamic adjustment strategy and summarize how the estimation of unidentified tags and control of frame length is improvised in dynamic frame slotted aloha algorithm. The interrogation process is similar to the FSA algorithm.

First the reader sends the query command with Q_i value which gives the number of slots in a frame ($N = 2^{Qi}$) that tags has to choose the slots between 0 to N-1 to send their information. Further, the reader takes statistics of the frame such as success, collision and idle slots and at the end of the frame it updates its frame size as $N = 3.49 \times C$ and again starts the new interrogation process until all the tags are identified.

B. Exponential Random Partitioning-Frame Slotted Aloha (ERP-FSA) Algorithm

In ID-FSA, we proposed a dynamic frame size adjustment mechanism in which the frame size can be dynamically adjusted with the estimated number of tags. Similarly, to exploit the optimal frame length we implement a reverse technique in which the interrogating tags are adjusted in such a way that the applied fixed frame size becomes optimal. Lee et. al. in [9] tried to implement the grouping mechanism to adjust the number of tags with the frame size. However, Lee el. al. did not approach for the optimal case in which the given frame size will be optimal for interrogating number of tags.

Let N denotes the number of slots in a static frame to read a set of n tags. In ID-FSA, we calculated that the frame size will be optimal if $N = 3.49 \times C$ i.e., the frame size will not be optimal if $N < 3.49 \times C$. This implies that the maximum number of collided slots that has been occurred in a frame to make the given frame size optimal is $C < (1/3.49) \times N$ i.e., $C < 0.29 \times N$. If a frame has more than $0.29 \times N$ collided slots, the given frame will not be optimal so we have to reduce the contending tag population.

We used the above condition as a threshold value in the ERP - FSA algorithm to partition the given set of tags. Assume that the given set of tag is partitioned exponentially with the access probability, P_a. For the first frame, $P_a = 1$ giving priority to all the tags to access the frame. Fig. 4-3 shows the partitioning model in ERP-FSA algorithm. If the algorithm determines that, comparing with the frame size, the unread tags cannot be optimally accommodated in the given frame size, then it limits the number of collided tags. If $C > 0.29 \times N$ (Condition A), then $P_a = 1/2$, which implies that the access probability of the interrogating tags are reduced by 50%, so in the second frame the accessing number of tags will be reduced by half. Similarly, until the given condition A is correct, the access probability will be reduced exponentially and if the condition A is not fulfilled (Condition B) i.e., $C \leq 0.29 \times N$, we can confirm that the given frame size is optimal for the partitioned number of tags. Therefore, the reader will interrogate all the tags in that partitioned group regulating the fixed frame size. Whenever, all the tags in that group are interrogated, P_a will be increased by 2 to accommodate the just enough number of tags for further interrogation. The interrogation process is similar to BFSA Algorithm in which the reader transmits the fixed frame size in every query command and the tag randomly selects one slot to send its information. The tags can only transmit once in each frame and if it is not recognized in that frame it has to wait for another frame to transmit its information.

Fig.4-4 depicts the evolution of the access probability of different tag population when the given fixed frame size is 32. Initially for all set of tags (100 - 500) the access probability will be decreased exponentially up to certain access probability level so that the contending number of tags is reduced sufficiently.

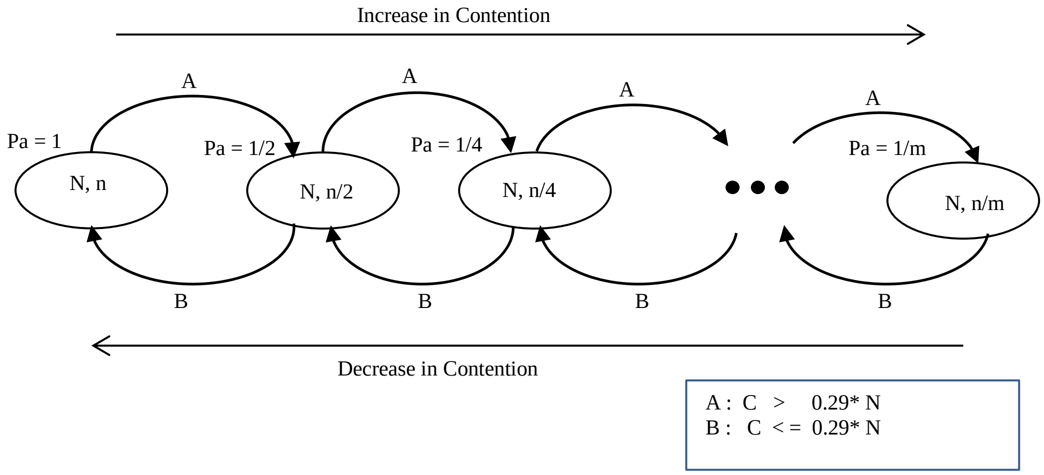


Figure 4-3. Exponential Random Partitioning Model

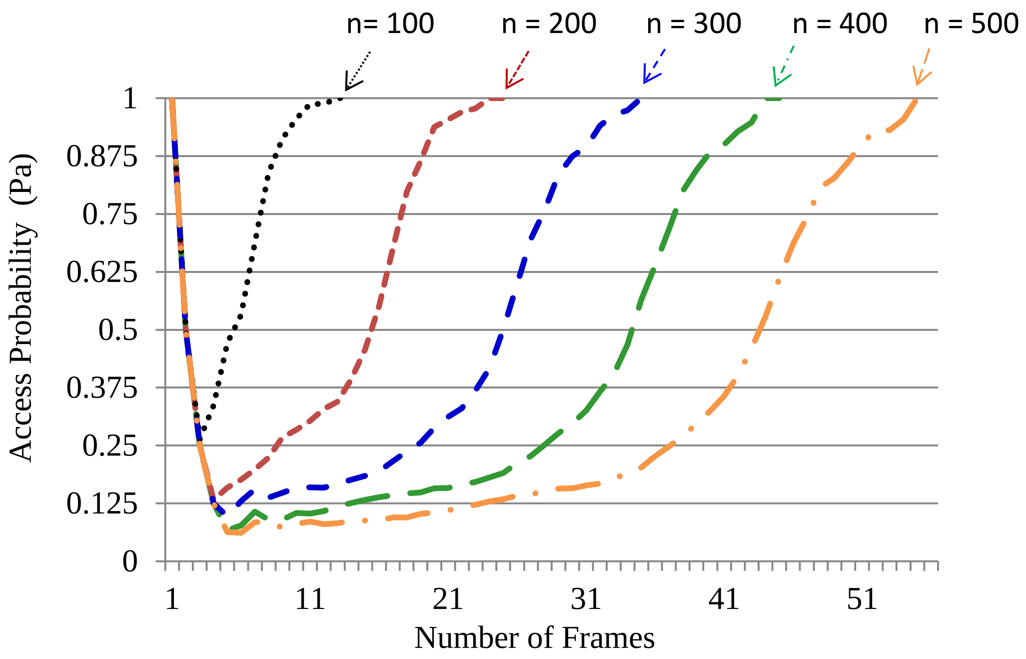


Fig 4-4 Evolution of Access Probability (P_a) of different tag population at (N = 32)

In Fig. 4-4 we can observe that for 100 tags the graph is again increasing exponentially after reaching at certain point however, for higher tag population after reaching a certain level (< 0.125) the graph is gradually increasing. This is because the reader has to maintain the contending tag population in such a way that the given frame size always becomes optimal.

V. Performance Analysis

In this section we present the simulation results obtained from our proposed schemes and compared with other protocols. We compared our results with Schoute's dynamic frame adjustment technique, conventional EPC global G2 protocol and Floerkemeier's scheme. In EPC Global G2 protocol we have implemented the slot count Q selection algorithm technique in which the initial Q value is updated on a slot by slot basis as given in its example of Annex D [8]. The Floerkemeier's technique is improvised slot count Q selection algorithm which uses the Bayesian slot-by-slot updating technique. Similarly in the Schoute's DFSA algorithm we dynamically adjust the frame size $N = 2.39 \times C$ in each frame.

Note that in EPC-Global G2 protocol we have implemented the slot count Q selection algorithm in which the current frame size Q_{fp} is incremented by x whenever the collision occurs and decremented by x when empty slot occurs. Then the reader sends *QueryAdjust* command and tag has to select a new random value within 0 to N-1. So the random value chosen by the tags are dynamically adjusted rather than the frame size. Similarly, we have implemented same technique in Floerkemeier's scheme in which x value is updated as $x= 0.8/ Q$ instead of choosing the value from the range (0.1, 0.5) as in the EPC Global G2 protocol.

A. Simulation Environment

We have developed a system level simulator on Matlab that can characterize the proposed RFID model. In our simulator, we limit the choice of frame size to 8, 32 and 128 by selecting Q_i = 3, 5 and 7 for n tags, for example 10-100 tags, and iterated each tag population 1000 times in order to converge the simulation results. The simulator allows users to enter the interrogating number of tags and the initial frame size. The tags will pick up a slot randomly and respond to the reader's query. More than one tag responding in a particular slot will result into collision. The collided tags are to be interrogated again until all the tags are identified. Each slot responded with only one tag is the successful slot. Here we assume the case in which there is no interference and no capture effect and all the tags will transmit only in the selected slot. We have used evaluation parameters as given in Table 5-1. Further, we checked the performance of the system in two different tag environments; sparse tag environment (10-100) and Dense tag environment (100-1000).

Table 5-1 Parameters used in our evaluation

Description	Value	Description	Value
Simulation tool	Matlab	EPC	96 bits
Number of tags	10 – 100, 100-1000	FS (Frame Sync)	100 μs
Qi (Initial Frame Size)	3, 5, 7	T1	125 μs
Number of iterations	1000	T2	62.5 μs
QRep	4 bits	T3	62.5 μs
x	0.3	Data Rate	40 kbps
QueryAdjust	9 bits	P (preamble)	6 bits
ACK	18 bits	RN16	16 bits
CRC16	16 bits	PC	16 bits

B. Performance Metrics

Time System Efficiency

Although we have differentiated the precise time system efficiency (PTSE) and time system efficiency (TSE) in chapter 3. Here, for our convenience we used the metric Time System Efficiency (TSE) as defined similar to our PTSE. It incorporates both the number of slots and its time duration so that the evaluated performance is more reliable. The TSE is defined as the total time duration for successful slots divided by the total time consumed by the system to read all the tags.

$$TSE = \frac{S \times T_S}{S \times T_S + I \times T_I + C \times T_C}. \tag{29}$$

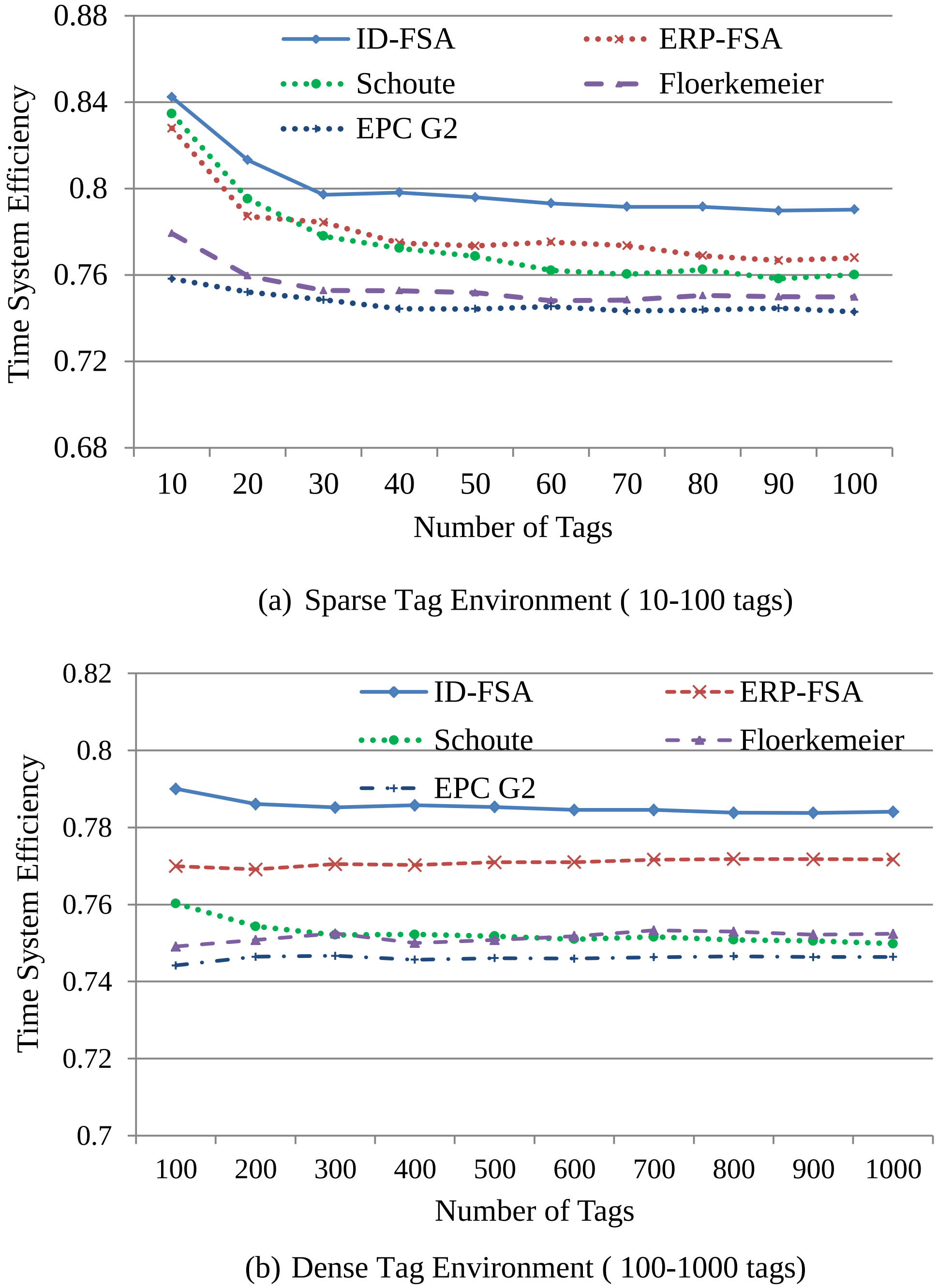
Where S, C, and I are the total number of success, collision and Idle slots occurred during the whole identification process. In all of the compared algorithms, we have considered different slot lengths (T_S, T_I, T_C) for all three types of events.

C. Results and Discussion

In this section, we evaluate the performance (time system efficiency) of our proposed ID-FSA algorithm and ERP-FSA algorithm compared with other techniques such as Schoute's dynamic frame adjustment technique, conventional EPC global G2 protocol and Floerkemeier's technique by varying the initial frame size values.

Fig. 5-1 (a) and (b) depicts the time system efficiency of five compared algorithms with initial frame size N = 8. With increasing number of tag population both ERP-FSA and ID-FSA algorithm achieves improved performance results compared with other three algorithms in both sparse and dense tag environment. This means that potentially both algorithms decrease the collision rate and increases the performance of the system. The performance improvement of the ID-FSA algorithm is more than 3% for dense tag environment. Similarly ERP-FSA has also gained more than 2% improvement compared with other algorithms in dense tag environment.

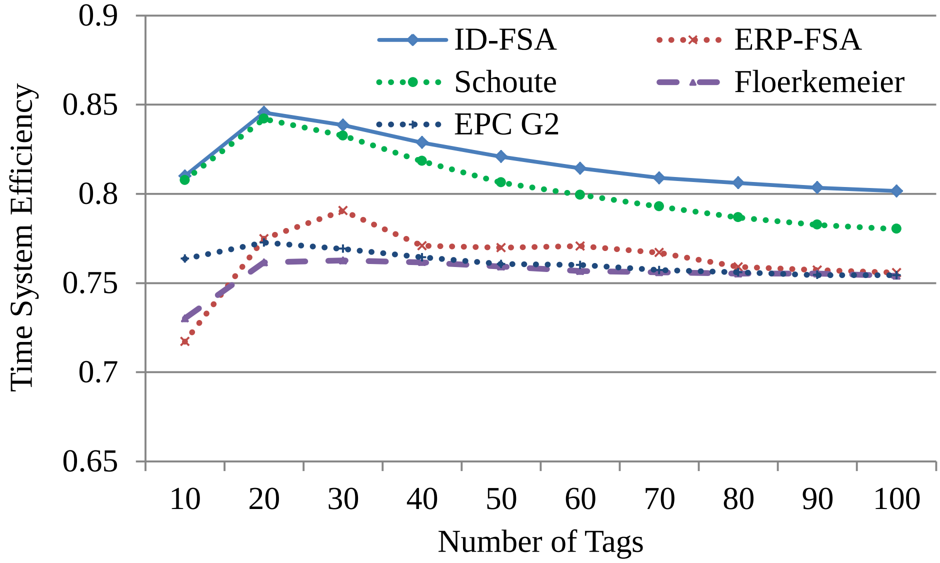
Note that the time system efficiency of the ERP-FSA algorithm is lower than the ID-FSA algorithm. This is because the ERP-FSA algorithm uses the static frame size and initially the collision ratio is high in each frame until the tags are sufficiently decreased.



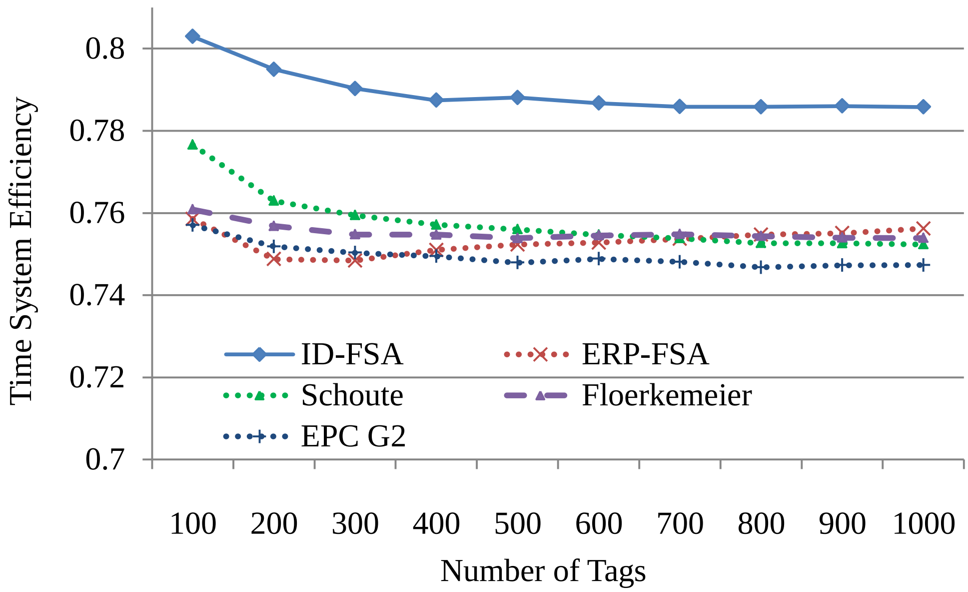
(a) Sparse Tag Environment (10-100 tags)

(b) Dense Tag Environment (100-1000 tags)

Figure 5-1: Comparison of the performance (Time System Efficiency) of different algorithms having initial frame size N = 8

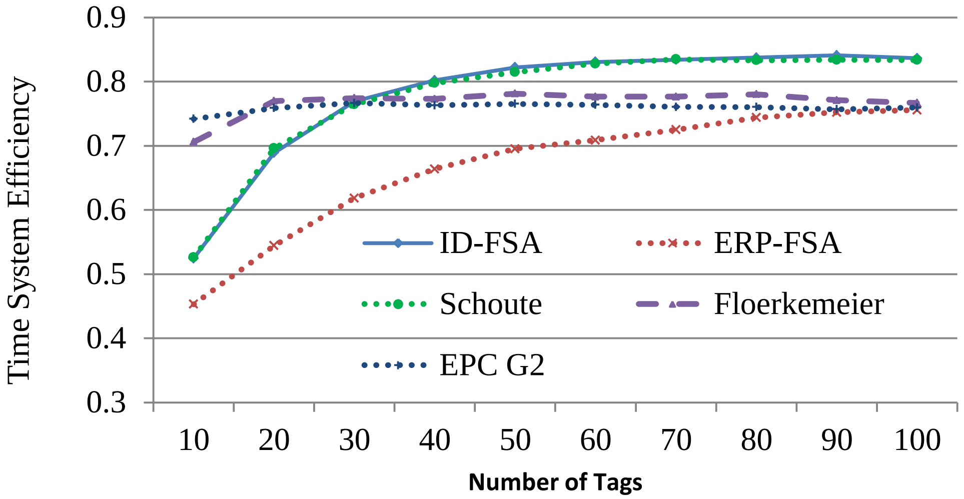


(a) Sparse Tag Environment (10-100 tags)

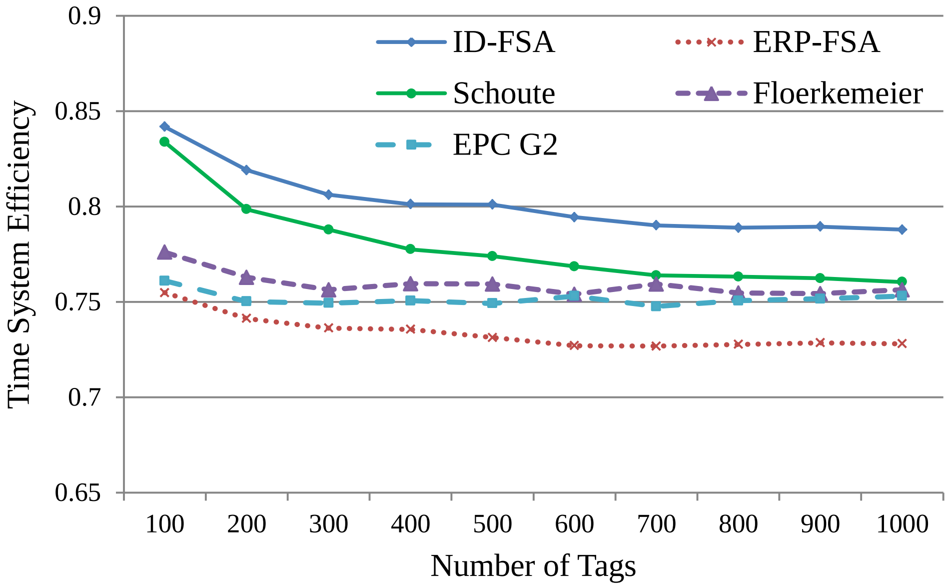


(b) Dense Tag Environment (100-100 tags)

Figure 5-2: Comparison of the performance (Time System Efficiency) of different algorithms having initial frame size N = 32



(a) Sparse Tag Environment (10-100 tags)



(b) Dense Tag Environment (100- 1000 tags)

Figure 5-3: Comparison of the performance (Time System Efficiency) of different algorithms having initial frame size N = 128

Similarly, Fig. 5-2 (a) depicts that with the increase in the initial frame size (N = 32) the performance of the ID-FSA and Schoute's algorithm comes closer for sparse tag population (< 30). This is due to the fact that the initial frame size can easily accommodate the tags which are less in quantity than the number of slots used in frame. The performance of the ID-FSA algorithm is consistent when the number of tags increases as observed in Fig. 5-2 (b). However with the use of unreliable and non-optimal frame length adjustment technique the performance of other algorithms rapidly decreases.

On the other hand, the ERP-FSA algorithm, that has to implement a large number of static frames initially, has more collision slots in dense tag environment when N = 32. Also when the tag population is very large (> 700) then the overhead during a frame size adjustment is amortized and we can see gradual performance improvement.

In Fig 5-3 (a), as the initial frame size has been increased (N = 128) the performance of the ID-FSA and Schoute's algorithm seems to have equal performance for the sparse tag environment. This is because of the two reasons: 1. Initial frame size is sufficient for accommodating such sparse tag population and 2. Adjustment of frame size for such small quantity of tag population doesn't differ much in ID-FSA and Schoute's algorithm.

When the number of tags increases, as shown in Fig 5-3 (b) the performance of ID-FSA algorithm is better than other algorithms. However, the performance of the ERP - FSA algorithm has less performance compared with other algorithms. This is because of the large frame size; either it has to waste a large number of idle slots in the sparse tag environment or to endure large collided slots initially and large number of idle slots during the read cycles, in dense tag environment.

Note that, in EPC Global G2 and Floerkemeier's scheme we have implemented slot by slot updating scheme in which the reader has to use QueryAdjust command many times during slot adjustment. Therefore, due to QueryAdjust command the overhead of the system will be increased thereby decreasing the performance of the system.

From our simulation results mainly two phenomena have to be noted. The first one is that the ID-FSA algorithm has improved performance results for any number of tag populations compared with other algorithms. This justifies that our approach of adopting the optimal frame size for estimated number of tags has some potential benefits in improvising the performance of the RFID system. The second phenomenon is that the performance of the ERP-FSA algorithm decreases with the increase in the frame size. This is because more static frames are wasted in adjusting the tag population which creates a large proportion of collision slots and results in a significant decrease in performance when frame size is large. However ERP-FSA algorithm, which performs well when the frame size is small, has also some potential benefits such as it doesn't add much overhead and complexity in the RFID system as compared with EPC-G2 and Floerkemeier's scheme.

VI. Conclusions

As the wireless access technologies are remarkably growing, RFID system are also being used comprehensively nowadays. While being used as a promising technology for wireless object identification, RFID system come-up with some challenges that has to be studied carefully. One of the major problems in RFID system is that the reader cannot decode the information from the tags, if more than one tag transmits their information concurrently to the reader, which is known as the collision problem. Therefore, designing and optimizing Anti-Collision Algorithms are fundamental to the effective use of RFID system.

In this thesis, we first reported an accurate analytical model to estimate the tag identification efficiency of the FSA based anti-collision algorithm in chapter 3. The proposed model improves the conventional model not only by accurately differentiating the timing durations of success, collision and idle events but also by considering the physical layer capture phenomenon. Through detailed numerical analysis, we have shown that the conventional model overestimates the time system efficiency of the static FSA-based RFID system when the tag population is low and vice versa. In addition, the conventional model underestimates the time system efficiency of the dynamic FSA based RFID system regardless of the tag population size.

Furthermore, in chapter 4 we presented two Collision Reduction schemes that exploit the initially proposed precise-optimal frame length and efforts to maximize the system performance. First, an Improvised Dynamic-Frame Slotted Aloha (ID-FSA) algorithm has been proposed which optimally assigns precise-optimal frame length for the next frame based on estimated number of collided tags from previous frame. Second, Exponential Random Partitioning – Frame Slotted Aloha (ERP-

FSA) Algorithm has been proposed which exponentially reduces the tag population based on the information of the collided slots. This algorithm uses the fixed frame size and reduces the contending tag population till the partitioned group of tags is optimally equivalent to the frame length. Detailed simulation analysis using Matlab simulator has revealed that the ID-FSA algorithm, which is more suitable for handling any number of contending tags, has performance superiority in terms of time system efficiency even in the dense tag environment and at various initial frame lengths. On the other hand, ERP-FSA algorithm performs well only when the fixed frame size is small. Therefore, the ERP - FSA algorithm can be adopted in Sparse RFID systems where we can adjust the least initial frame size. Moreover, the ID-FSA algorithm can be simply adopted in any RFID systems without additional overhead and complexity to improve the performance of the system.

Current proposals for RFID systems has been investigated assuming ideal interrogation environment. However, a more challenging problem is evaluating the performance in real time scenario considering the parameters such as capture effect and channel error. Moreover, there are several tag estimation techniques that has been implement in different tag population environment. Therefore, further research is necessary to find the reliable tag estimation techniques for different tag environments, implemt them in the proposed schemes and simulate the proposed algorithms in a test bed setting.

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