UTILIZING PHYSICAL LAYER INFORMATION TO IMPROVE RFID TAG IDENTIFICATION

by

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My first encounter with this field was a year and a half ago when I took Daniel Engels' RFID course. Our informal yet highly informative discussions paved my way into the exciting field of RFID and showed me the unlimited opportunities that exist. Dan's enthusiasm is infectious and his quest for constant improvement has made me realize my true potential. I wish to thank him for showing me the true meaning of research. His advice in all walks of life has been of great help.

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ABSTRACT

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Radio-frequency identification (RFID) systems are designed for fast and accurate identification of multiple RFID tags. Their performance depends on the effective detection and resolution of communication collisions caused by the presence of multiple tags in the readers field. Present RFID protocols do not rely upon the received physical waveform obtained during a collision for either collision resolution or improved identification rate. This signal contains important information that is often ignored or otherwise discarded.

In this thesis I analyze the physical layer information extracted from a collision waveform from the ISO-18000-6C protocol and identify potentially performance enhancing information contained therein. Utilization of this information to increase the tag identification rate is examined and the effectiveness of these approaches is analyzed. We find that utilizing the information contained within the physical waveforms can improve the identification rate for ISO 18000-6C systems by as much as 21%. By modifying the protocol to explicitly take advantage of this waveform information, we estimate that another 10% identification rate improvement may be achieved.

This thesis proposes a method of using the physical layer signal from a collision to detect the existence of a weak tag in the presence of stronger tag to improve the reliability of the present protocol. The performance of random number generator on the chip and may be non-ideal leading to a non-uniform distribution. The effect of this deviation from the theoretical values and its effect on the performance of the protocol is analyzed by simulation. Output of the random number generator of some standard RFID tags is also evaluated.

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CHAPTER 1

INTRODUCTION

Radio-Frequency Identification (RFID) technology is an automatic identification technology (Auto-ID) which uses radio waves for the communication and retrieval of identification data. Bar code identification is the most widely adopted Auto-ID technology and is used is almost all walks of life. An RFID system consists of an interrogator (reader) communicating with a tag which is affixed to the object to be identified. Use of electromagnetic waves for identification gives RFID many advantages over bar codes. RFID allows identification of multiple items at a very high speed whereas bar codes can only identify a single item at a time. RFID systems also offer higher memory capacity and a longer read range.

RFID systems operate over a wide range of frequencies from 100KHz to well over 5GHz. They can be classified as either active or passive systems depending upon the type of tags used. This thesis will focus on the UHF passive RFID system operating over the 902-928MHz ISM band.

1.1 Background

Reliability and speed are the two major driving factors for ongoing RFID research. Multiple tag identification capability of RFID systems allow them to be fast. However an RFID tag has very limited resources and hence limited functionality so all the tags within a reader's field attempt to communicate with the reader as soon as they get energized. This causes a communication collision and disrupts the identification process. To overcome this problem, algorithms called anti-collision algorithms have been developed. Anti-collision algortihms do not completely remove collisions but try to minimize their occurence. Reduction of collisions is a key factor in determining the performance and efficiency of an RFID system.

Passive UHF RFID systems follow the EPC Class 1 Generation 2 air interface protocol for communication. This protocol is an interrogator talks first protocol. This means that any communication between the tags and the reader is initiated and controlled by the reader. Thus the efficiency of the system depends mainly on the ability of the reader to understand its environment and issue appropriate commands. At the outset of the identification process the reader is unaware of the tags in its field. There can be 0,1,10, 100 or even 1000 tags within range. Obviously the performance of the anti-collision algorithm will not be the same in all the above cases. This thesis suggests a method to effectively estimate the number of tags which can then be used to fine tune the anti-collision algorithm.

Passive RFID systems are also limited by the RF power output restrictions on the readers. The readers operate in the ISM band and can radiate a maximum of 1-4 Watt of power. Passive tags rely on the reader for power and reply by backscattering a very weak signal. This backscattered power influences the range and reliability of the system as noise can corrupt signals with insufficient power. Distant tags can thus be hidden from the reader although they can hear the reader and reply to its commands. This thesis proposes a way to minimize this occurence and hence increase the reliability of the process.

RFID tags are generally in the form of adhesive labels or strips with most of the area being occupied by the tag antenna. The actual integrated circuit on a tag occupies an area less than 1mm x 1mm. Furthermore, relative orientation between the tag and reader antennas affects the power available to the tag due to electromagnetic wave polarization. Environmental factors such liquids and metals cause tag detuning and signal absorption or reflection which further degrades performance. These factors require tags to have low complexity which prevents use of eloquent algorithms for random number generation.

1.2 Motivation

The EPC Class 1 Gen. 2 protocol detects a collision at the Medium Access (MAC) communication layer but does not utilize the physical layer signal. This signal contains important information such as the number of tags involved in the collision. Analysis of the signal also gives information such as the distance of the tag which would otherwise be discarded. Earlier attempts use probabilstic approaches to estimate the number of tags within a reader's range. RFID readers generally use digital signal processing and have upconverters and downconverters for conversion between a high radio frequency and a low intermediate frequency. The downconversion of the received signal results in a complex waveform with in-phase (I) and quadrature-phase (Q) waveforms. This thesis proposes a method to use information extracted from the I-Q plot to give a better estimate of the number of tags and hence increase the system efficiency.

RFID Readers use the received waveform and decode the information sent by the tag which is a 16-bit random number (RN16). In the event of a collision between a strong tag and a weak tag, the reader may detect only the presence of the stronger tag and completely miss the other tag. This thesis uses the I-Q plot to detect the presence of a weak signal. This allows the reader to acknowledge the presence of a weak tag and take appropriate steps to identify it.

In the event of a collision between two tags, the I-Q plot can be used to separate the two signals involved in the collision. Application of digital signal processing techniques like signal separation for extracting RN16s and their feasibilty is discussed.

Limitations of the present protocol enable acknowledgement of only a single tag in a slot. Thus even if the two colliding RN16s are correctly decoded, only one of them can proceed with the identification process. This thesis suggests a modification to the present protocol and estimates the performance improvement possible.

The effect of a bias in the random number generator of an RFID chip is analyzed by running a simulation. Performance of random number generators of some standard tags is evaluated by using statistical methods.

CHAPTER 2

PASSIVE UHF RFID SYSTEMS

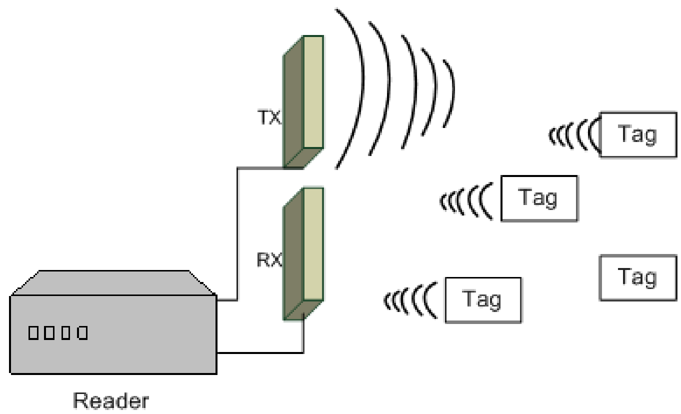

Figure 2.1. RFID system setup.

2.1 RFID Reader

UHF RFID systems use the EPC Class 1 Gen. 2 protocol which is a reader talks first protocol. The reader therefore controls the entire identification process and so is an important component of the system. It is the readers job to power up the tags by sending a carrier wave whose frequency lies in the ISM band. RFID readers amplitude shift keying or phase shift keying. Readers energize the tags in their field and identify them by starting an inventory round. Upon successful completion of the round the reader has a list of the EPC ids of each tag. This EPC is a unique 96-bit number which identifies every tag. The reader then sends this information to the middleware which retrieves the product information from a central database.

RFID readers operate in the ISM band and so they need to follow FCC guidelines for carrier power and frequency. Readers need to implement frequency hopping to avoid jamming transmissions from other devices. Maximum power is limited to 4W EIRP by the FCC. Using directional antennas further reduces this allowable power. This is the determining factor for the read range of a tag.

2.2 Passive UHF RFID Tag

Passive RFID tags rely entirely on the reader as their power source. Passive HF tags operate on the principle of electromagnetic induction and opearte in the near field of the reader. This restricts their range to 10-15 cm. Passive UHF tags on the other hand operate on the principle of backscatter. This is similar to the functionality of a RADAR. These tags can be read up to 10m away, and they have lower production costs which ensures application to less expensive merchandise. Fig. 2.2 and Fig. 2.3 show two different types of UHF RFID tags. These tags consist of an RFID chip and an antenna. The antenna pattern differs from tag to tag and depends on where the RFID system is used. The material of the tag also differs according to its application. Tags which are applied on metals have a thicker base to maintain sufficient distance between the tag chip and the metal. This is done to reduce the detuning effect of metals on the tag.

2.3 Collisions

RFID systems often have multiple tags responding for brief periods separated by pauses of unequal length. In many applications a number of items have tags attached to them. All these items need to be read as unique and distinct instances. The realization of such a system poses problems since the reader has to prevent

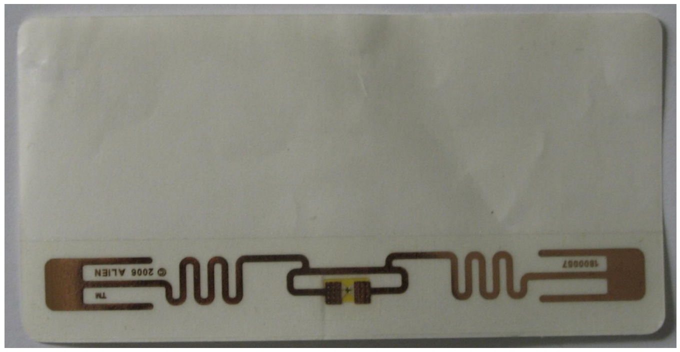

Figure 2.2. Alien Squiggle Tag.

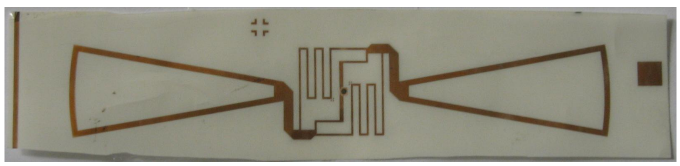

Figure 2.3. Avery Dennison Bow-Tie Tag.

data arriving from different tags from colliding with each other. An algorithm that facilitates the reception of data from multiple tags is called an anti-collision algorithm.

Most anti-collision algorithms are deployed in an environment where certain important environmental data, such as the number of tags participating in the desired process, are unknown or variable. Algorithms, such as a tag estimation algorithm, may be constructed to assist the basic anti-collision algorithm so as to provide accurate information in this otherwise unknown world.

Single reader-multiple tag collision is caused due to presence of multiple tags trying to communicate with a single reader. The simultaneous responses from multiple tags may prevent the reader from interpreting the communication signals correctly. In tree based protocols, which are based on the collision resolution algorithm, tags, which transmit at the same time, form a set. When a set causes collision, the mechanisms split it into two subsets and attempt to recognize two subsets in turn. The binary tree protocol, which uses random numbers for splitting, is adopted as the standard for RFID anti-collision in ISO/IEC 18000 Part 6B. The query tree protocol splits a set of tags by the reader's queries. Although tree-based protocols do not cause tag starvation, they have relatively long identification delay due to the splitting procedure starting from one set including all tags [3] [4].

CHAPTER 3

ISO 18000-6C PROTOCOL

The ISO 18000-6C protocol, also known as the EPC Class-1 Generation-2 passive RFID protocol [1] operates in the UHF frequency band with an effective identification range of 5 - 10m. The anti collision algorithm is a dynamic framed slotted aloha algorithm where tags respond to a reader in a backscattered fashion. The basic optimality problem of this anti-collision algorithm is to dynamically assign an optimum number of slots by exchanging parameter Q communicated from the reader to the tags. The optimum Q value is equal to the (unknown by the reader) number of tags in the reader's communication zone [5].

The ISO 18000-6C tag identification procedure begins with an inventory round. The reader first sends a Query command to all the tags which includes a parameter Q. Each tag receiving the Query command randomly selects an integer in the range of 0 to 2^{Q} -1 as its own slot number and responds with a 16 bit random number called the RN16 in the corresponding slot.

The EPC Class-1 Generation-2 protocol document [1] contains a procedure for estimating the number of tags and updating Q appropriately. This procedure is shown in Figure 3.1. In this procedure, the reader updates parameter Q by a step C according to the tags response and broadcasts the updated parameter Q to all the tags together with a command after each reading slot. Knowing the exact number of tags in the field allows an optimal choice of Q. Therefore, knowing number of tags is critical to the optimal use of the anti-collision algorithm. However, as parameter Q is updated after every reading slot, it dynamically adjusts the number of slots, but

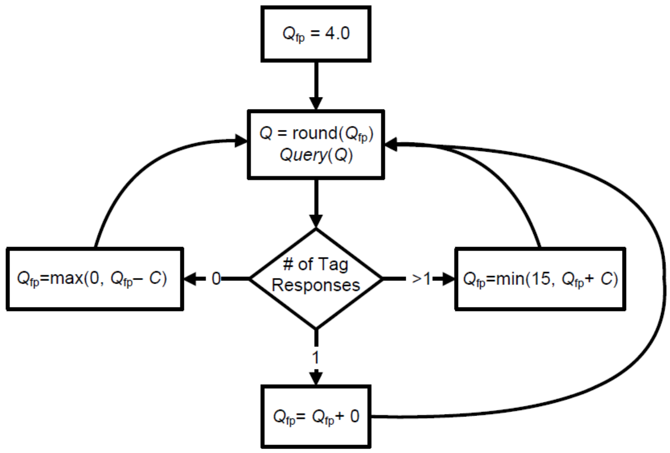

Figure 3.1. Slot count (Q) selection algorithm [1].

it needs time to converge to the optimal value. This convergence time reduces the reading efficiency.

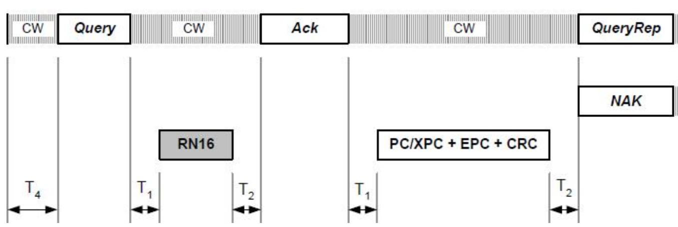

Figure 3.2. Inventory sequence [1].

Figure 3.2 illustrates the sequence of commands between the RFID reader and the tags during a portion of the inventory process. The upper part of the figure shows the transmissions sent by the reader and the shaded boxes represent the tag transmissions.

The reader begins the data exchange by starting an *Inventory* round for tag inventory and subsequent access. It then sends a *Query* command which contains the slot-count parameter Q. Upon receipt of this parameter, all the tags pick a slot between 0 and 2^Q-1. Tags that pick a zero shall transition to the reply state and reply immediately. Tags that pick a nonzero value shall transition to the arbitrate state and await a QueryAdjust or a QueryRep command. Assuming that a single Tag replies, the query-response algorithm proceeds as follows:

1. The Tag backscatters an RN16 as it enters reply.
2. The Interrogator acknowledges the Tag with an ACK containing this same RN16.
3. The acknowledged Tag transitions to the acknowledged state, backscattering its PC, EPC, and CRC-16 [1].

In the ISO 18000-6C protocol, readers communicate with tags using DSB-ASK or PR-ASK with Pulse Interval Encoding(PIE). The tag to reader communication uses ASK modulation and FM0(bi-phase space) or Miller encoding for the data. Figure 3.3 shows the waveforms for FM0 encoding. FM0 inverts the baseband phase at every symbol boundary; a data-0 has an additional mid-symbol phase inversion. The duty cycle of a 00 or 11 sequence, measured at the modulator output, is a minimum of 45% and a maximum of 55%, with a nominal value of 50%. FM0 encoding has memory; consequently, the choice of FM0 sequences in Fig. 3.3 depends on prior transmissions. FM0 signaling always ends with a dummy data-1 bit at the end of a transmission. [1]

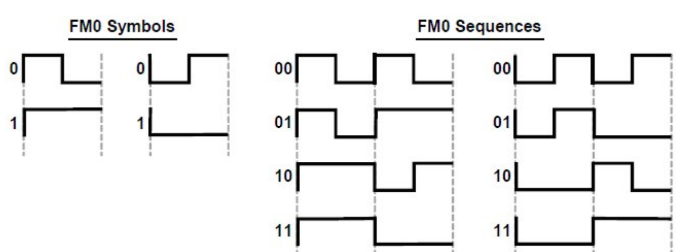

Figure 3.3. Tag to reader data encoding [1].

CHAPTER 4

RELATED WORK

Multiple tag identification is one of the major advantages of RFID systems. Passive UHF RFID systems use anti-collision algorithms that are modified versions of the ALOHA [6] protocol and hence are probabalistic in nature. This chapter describes previous approaches used to increase the identification rate of RFID systems using stochastic methods.

4.1 Tag identification in a static tag set

Tagged items in a shopping bag, items on a shelf in a store are examples of static tag sets. In such scenarios, the number of tags during the identification process remains constant and depending upon the number of tags present, tag identification comes to an end eventually.

4.1.1 Optimal Q value determination

Due to limitations on the computational complexity of an RFID tag, anti-collision protocols use frame sizes that are powers of 2. If the number of tags is known, the simplest method of choosing the number of slots is to choose the power of 2 greater than or equal to the number of tags. This approach is however inefficient since the tags use a random number generator to select a transmission slot. If the frame size is small and the number of tags is high, number of collisions will outnumber the number of tags correctly identified. This requires multiple rounds for complete identification of the tag set. On the other hand, a large frame size leads to long identification times even if the number of tags is small. Moreover this approach further degrades the identification efficiency when tags enter the reader's field once the identification round begins. These tags then have to wait a long duration till the entire round end and the next one begins.

In [5] , Vogt mentions that given N slots and n tags, the number of tags (l)occupying one slot follows a binomial distribution and is given by

$$l = \binom{n}{r} \cdot \left(\frac{1}{N}\right)^{r} \cdot \left(1 - \frac{1}{N}\right)^{n-r} \tag{4.1}$$

Thus substituting r= 0 in the above equation gives the number of empty slots for a particular pair of N and n. Similarly r= 1 gives the number of read slots and r=2 or more give the number of collided slots. This formula can be used to predict an optimum number of slots for known number of tags. These values can be precomputed and stored in a look-up table which the reader can then use at run-time to save computation time.

4.1.2 Tag population estimation

In the above section, a method for determining the optimum Q value was described. This method is suitable only when the number of tags is known a priori. In most cases like the shopping bag example, the number of tags is unknown. Tag population estimation is thus an important step for efficient identification. Vogt [5] describes a simple estimation function which gives a lower bound on the number of tags present (n_{lb}).

$$n_{lb} = s_r + 2 * s_c \tag{4.2}$$

where s_r is the number of read slots and s_c is the number of collided slots.

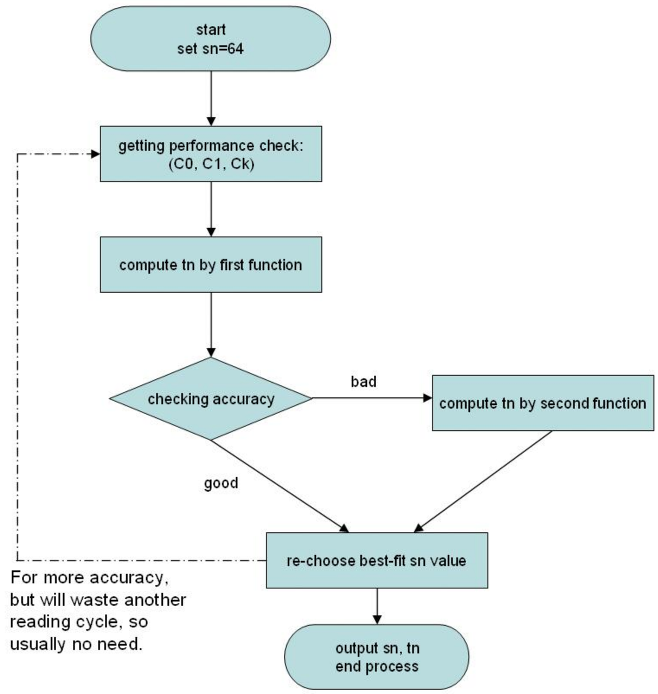

Figure 4.1. Two functioned estimation algorithm [2].

4.1.3 Two-functioned estimation

[2] presents a two-functioned estimation which claims an improved estimation over the previoulsy stated estimation function. This approach uses the tag estimation function described above and calculates the error. It then updates the Q value using equation 4.1 for an enhanced estimate and starts the new round. Fig. 4.1 describes this procedure.

4.2 Dynamic Tag set identification

In some RFID applications, tags enter and leave the reader's field continuously. A reader at a dock door or one reading items off a conveyor belt has a dynamic number of tags during the identification process. UHF RFID systems pose a more difficult problem as field nulls are created due to multipath and other environmental effects. Thus even tags within read range may vanish and reapper unxpectedly.

Framed ALOHA usually means that acknowledgements are sent only after the end of a frame and not in between but this is not true for RFID anti-collision protocols [7]. RFID protocols send a *QueryRep* command to signal the beginning of the next slot. By replacing this command with a *Query* command, a new round can be started instead. In [7], the estimate of the number of tags in the field is updated at the end of each slot as opposed to the end of a frame in previous approaches. The probability estimate of the number of tags replying is updated using a Bayesian approach.

CHAPTER 5

COMMUNICATION THEORY

The previous chapter discusses some of the approaches to improve tag identification rates. All of these approaches use probabilistic methods to estimate the state of the reader-tag system. Further, they use only high level information like the presence or absence of a collision. This chapter describes the nature of signals sent by a tag at the basic physical layer. Identification of important information relevant to the identification process and extracting this information from the collision signal is described in detail.

5.1 RCS parameters

Passive UHF RFID tags do not have their own source of power. They rely on the reader to provide them with power in order to enable their identification process. RFID protocols generally use amplitude modulation with Manchester or FM0 encoding of the data to be transmitted. A tag communicates with the reader by backscattering the incident RF carrier from the reader. Fig. 5.1 shows the internals of a passive UHF RFID tag. The signal received from the antenna is fed to a rectifier and voltage multiplier circuit. This part rectifies the incident carrier wave and stores it till there is sufficient energy to power up the tag chip. The tag chip contains all the processing circuitry of the tag. The amount of power backscattered by the tag depends on the effective impedance of the tag antenna. This impedance can have two states Z_{c1} and Z_{c2}. These two impedance states are responsible for the two radar cross-section states (RCS) of the tag. The tag chip can vary the tag antenna

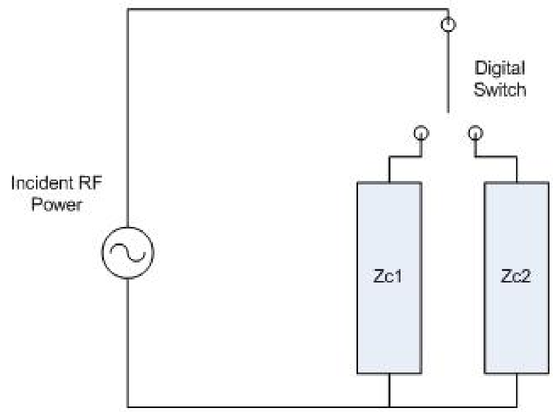

Figure 5.1. Passive tag structure.

impedance between one of the two RCS states and thus modulate the backscatterd signal. Fig. 5.2 shows the effect and importance of the two possibilities possible for the RCS states of the tag.

The above figures show the reader-tag communication waveforms after AM demodulation. One of the RCS states corresponds to a *0* being sent by the tag while the state corresponds to a *1*. The higher the separation between the tag states, higher is the tag read range.

5.2 I-Q plot

Digital signal processing is replacing analog techniques in many areas of electronic communication. This is mainly due to an increase in speed and a decrease in cost of signal processing hardware. RFID readers are radio transceivers operating in the UHF ISM band of 902-928 MHz. RFID readers use digital signal processing hardware for signal conversion and detection.Fig. 5.3 shows a conventional radio receiver and Fig. 5.4 shows a DSP based radio receiver. A conventional analog radio receiver uses a mixer which converts the incoming RF signal from the RF amplifier to the intermediate frequency (IF). The IF amplifier then feeds the demodulator which

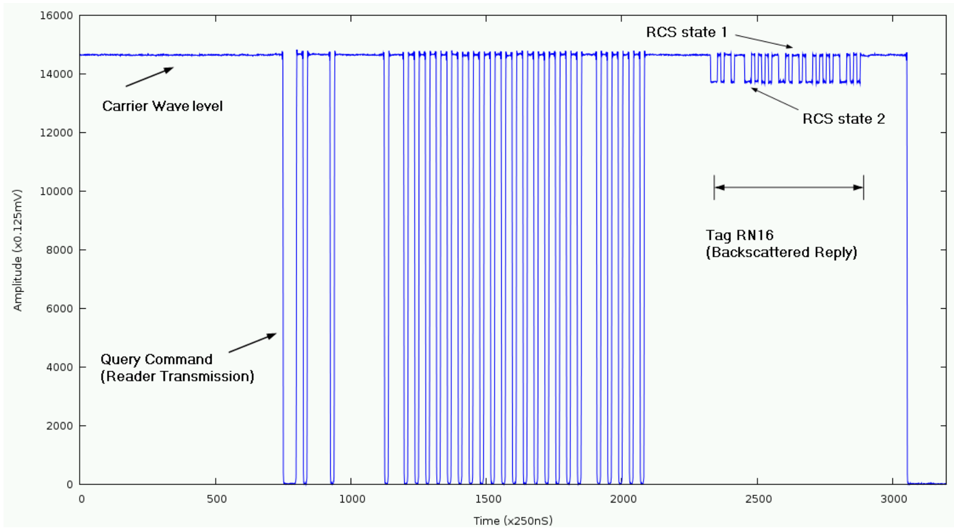

Figure 5.2. RCS states in tag waveform.

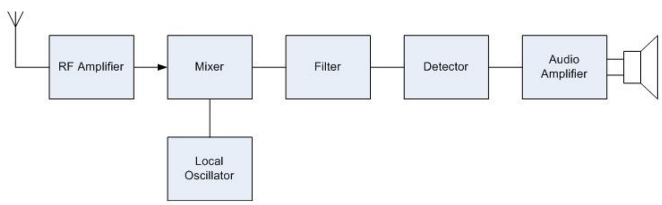

Figure 5.3. Conventional radio receiver.

recovers the baseband signal. A Digital radio uses an RF front end, a high speed analog to digital converter and a digital down converter (DDC). The DDC is typically used to convert an RF signal down to baseband. It does this by digitizing at a high sample rate, and then uses purely digital techniques like multiplication, decimation and filtering to recover the baseband signal. Fig. 5.5 shows a block diagram of a digital down converter. We observe that the input to the DDC is a real signal while the output from the DDC is a complex signal. The DDC stage accomplishes this by using a local oscillator that generates a complex version of the carrier, with precise 90-degree phase shift between its channels. The output signal thus is complex in nature and consists of an in-phase (I) and a quadrature phase(Q) component. Plotting

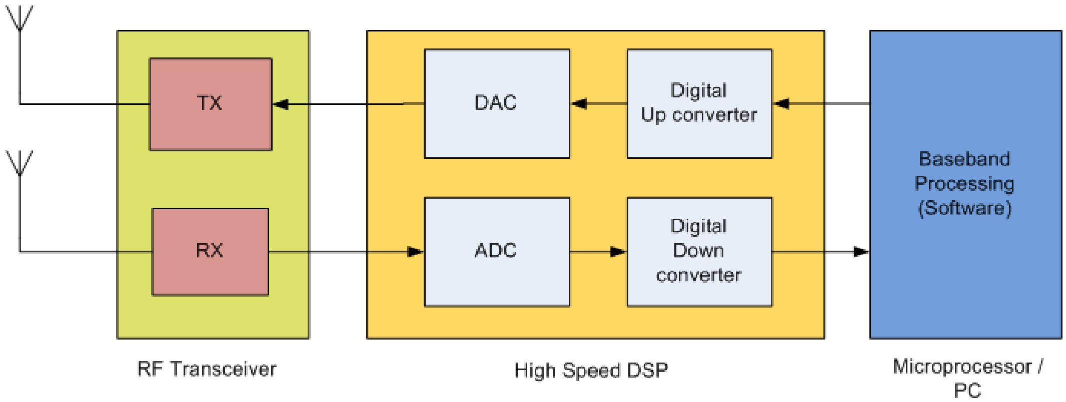

Figure 5.4. Software defined radio.

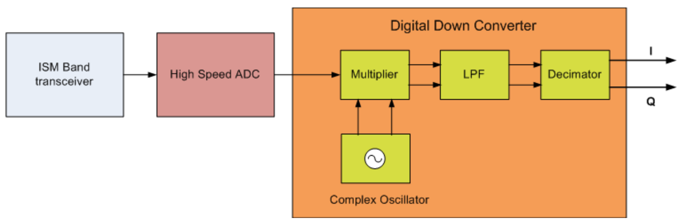

Figure 5.5. Digital down converter.

the I signal against the Q signal gives us the I-Q plot. Fig. 5.6 shows a typical RFID tag random number 16 (RN16) waveform and Fig. 5.7 the corresponding I-Q plot. We notice that the I-Q plot clearly shows the two RCS states of the tag.

Using a DDC has the following advantages:

Stability - not affected by temperature or manufacturing processes. With a DDC, theres never any tuning or component tolerance to worry about.

Software Control - all aspects of the DDC are controlled from software. The local oscillator can change frequency very rapidly indeed - in many cases a frequency change can take place on the next sample. Additionally, that frequency hop can be large since there is no settling time for the oscillator.

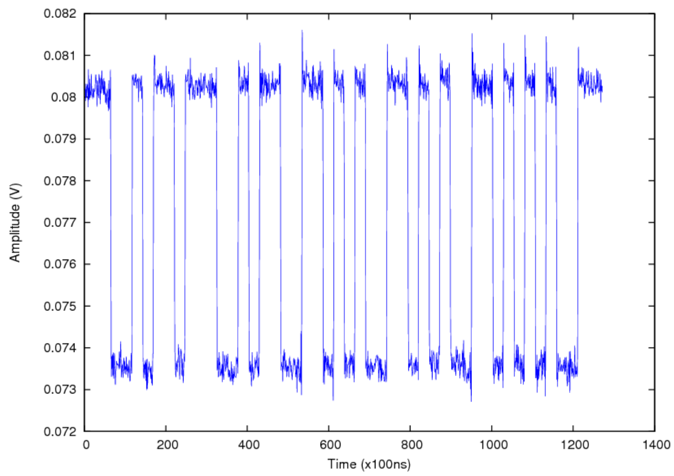

Figure 5.6. RN16 waveform of tag.

Size - A single ADC can feed many DDCs, a boon for multi-carrier applications. A single DDC can be implemented in part of an FPGA device, so multiple channels can be implemented or additional circuitry could also be added.

5.3 Signal separation

In a two tag collision, the RN16 waveforms sent by the two tags are incident at the reader antenna. The individual signals get superimposed and result in a received waveform with multiple RCS states. Fig. 5.8 shows the received waveform resulting from a two-tag collision. Each tag has 2 RCS states so N tags will have 2^N states. The above figure clearly shows the existence of 4 RCS states in a two tag collision. Due to the presence of noise introduced by the environment, the received RN16 waveform may not be clean. As seen in Fig. 5.6 there may be overshoots or undershoots in the waveform due to bandwidth issues. The waveform needs low pass filtering to remove this high frequency noise. The filter needs to be designed such that it eliminates the noise but retains the magnitude variations due to collision. Consider the half-bit time interval in FM0 to be 'x'; the length of a '1' is then 2x while that of

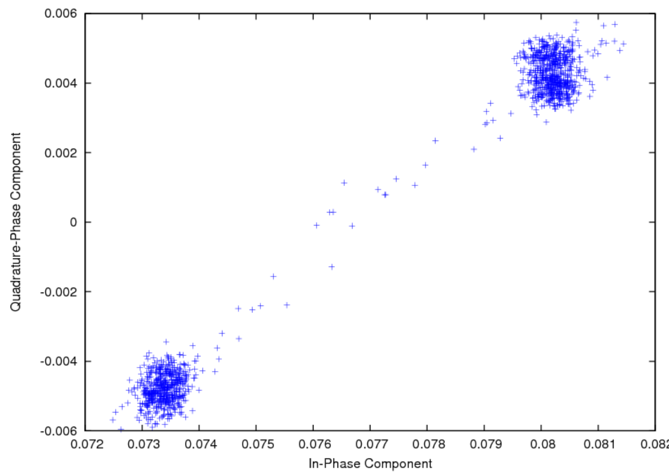

Figure 5.7. I-Q plot.

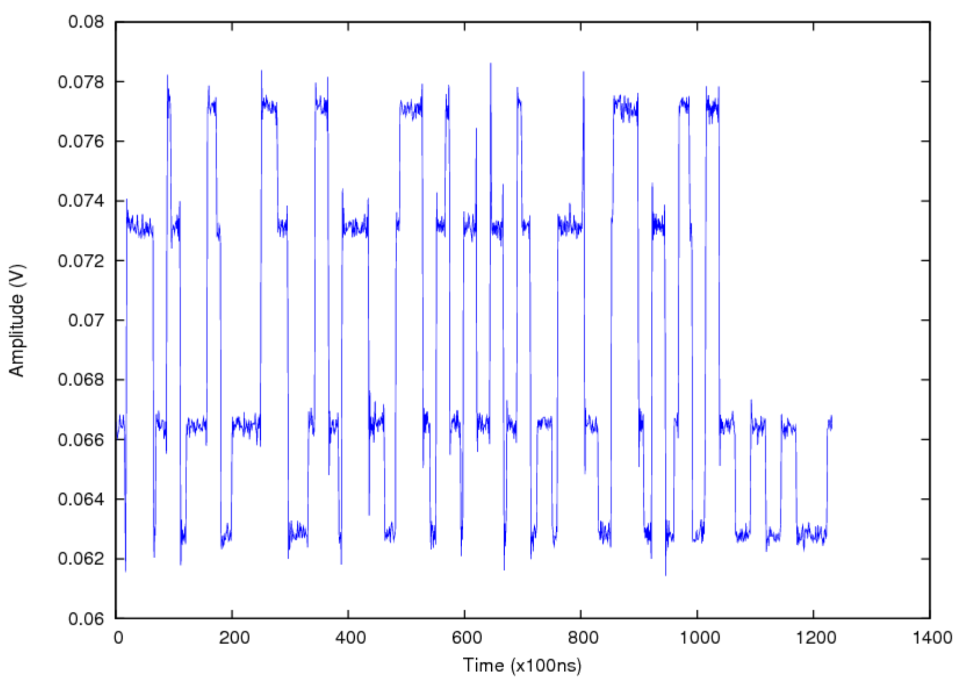

Figure 5.8. 2 tag collision.

a '0' is high for time x and low for time x. Thus a '0' represents a higher frequency and is given by 1/x. The fifth harmonic of this frequency can be a reasonable cutoff for the filter as the signals are square waves. Assuming that signals from the two tags have a negligible time lag, magnitude changes will occur at most every x length of time. Only the magnitude changes will be more as instead of two discrete levels we have four discrete levels during a collision.This situation is similar to a 4-QAM detector which has 4 constellations and so a minimum distance detector [8] can be used to resolve the signal into two separate digital signals.

The output of the minimum distance detector is then fed to the next stage which produces two separate signals using the power levels provided by the detector. The received power level is the superimposition of the power levels of the sinusoidal carriers. As the carriers will generally not be phase aligned, instantaneous power levels will vary. This generates noise in the received power envelopes of the tags. However this problem can be overcome as the tags transmit a digital signal with known bit times. Tag transmissions can be encoded using FM0 or miller encoding. Depending on the type of encoding used, the separated waveforms can be cleaned up and effect of noise induced due to errors in the waveform separation process.

CHAPTER 6

EXPERIMENTS AND RESULTS

6.1 Tag estimation from collision

As explained in the previous chapter, I-Q plot of the collision waveform shows the RCS states of the colliding tags. I-Q plot of a single tag has only 2 RCS states as shown in Fig. 6.1 below. If more tags are involved in a collision more RCS states

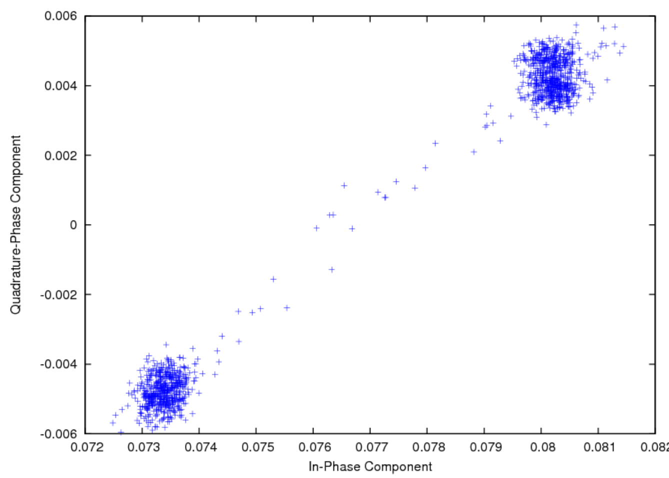

Figure 6.1. RN16 signal I-Q plot.

are observed. N tags will have 2^N states in the I-Q plot. Fig. 6.2 shows the I-Q plot for a 3 tag collision and Fig. 6.3 shows the I-Q plot for a 4 tag collision. As expected, the 3 tag case has $2^3 = 8$ RCS states and the 4 tag case has $2^4 = 16$ states. Thus the I-Q plot of the collided RN16 waveform can be used to detect the number of tags involved in the collision by counting the number of RCS states in it. Depending upon the number of tags, their orientation with respect to the reader antenna and

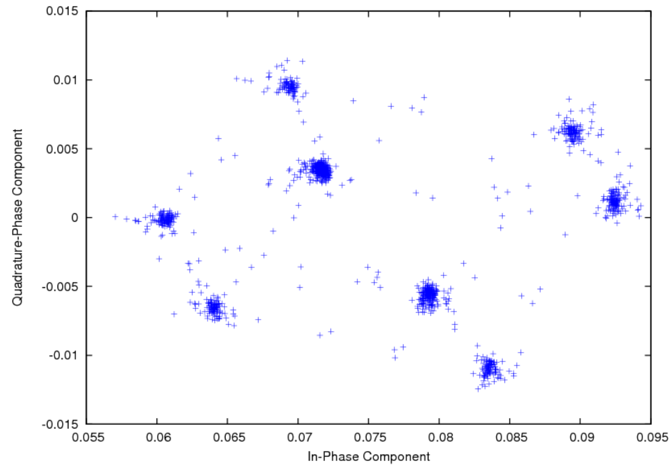

Figure 6.2. 3 tag collision.

environmental factors, the number of distinct states in the I-Q plot may be lesser than the expected number. Fig. 6.4 shows such a case where 3 tags were involved in the collision but due to overlapping of RCS states, the number of states observed is less than 8. In such cases, if the number of distinct states is greater than 2^N, we can be sure that N+1 tags exist. Thus if the number of states observed is 5, we can be sure that at least 3 tags are involved in the collision. Thus it becomes necessary to verify the practical accuracy of this approach. Experiments were performed by setting the reader's Q value to zero. A known number of tags were kept within the read range of the reader and I-Q plots were analysed to find the number of RCS states in them. This was used to estimate the number of tags involved in the collision. The tags were kept at random positions directly in front of the reader antenna. Readings were taken by changing the tag positions after each reading and noting the accuracy of the algorithm. The experiment was done for two cases:

1. 3 tags in range
2. 4 tags in range

Fig. 6.5 summarizes the results obtained. An accuracy of 71% was achieved with 3

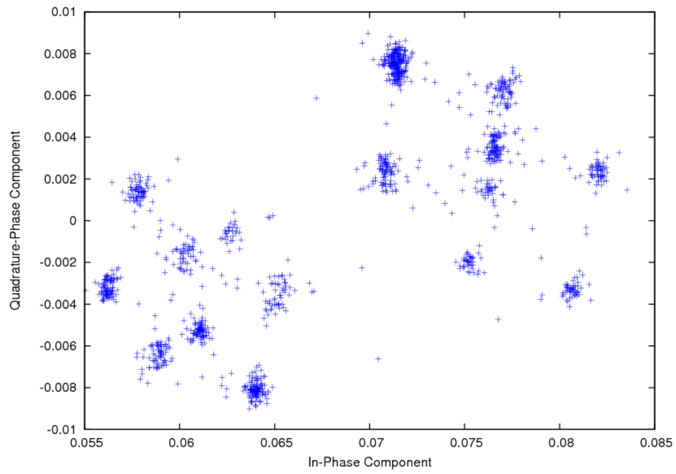

Figure 6.3. 4 tag collision.

tags in range while with 4 tags the accuracy was 73%.

6.2 Inventory round simulation

The algorithms described in this thesis aim to increase the identification rate of RFID systems. In this section, the performance various methods used is compared by running simulations of the tag identification process. For the simulation a set of 50 tags is assumed to be in the field of the reader. Initially a reader does not know the number of tags in the field and is required to guess a suitable Q value. In these simulations the initial Q value is set as 5 giving 32 slots. The time taken for complete identification of the tag set is computed by adding the time taken for each round. Time taken for a round with a specified Q value is calculated by adding the time required for each slot. The values used in our simulations are

Tquery = 10us

Tread = 42us

Tempty = 5us

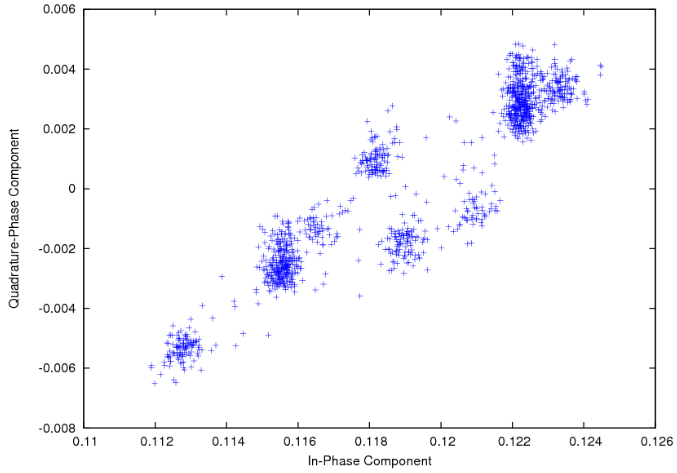

Figure 6.4. Overlapping RCS states.

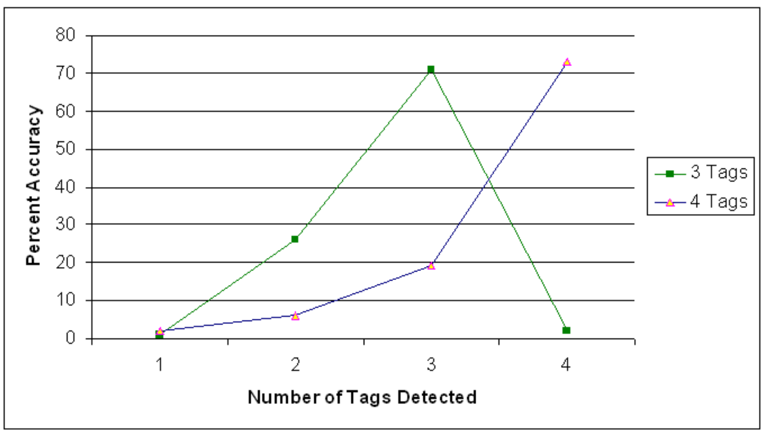

Figure 6.5. Collision detection accuracy.

Tcoll = 18us

The different methods used in the performance analysis and their simulation values are:

1. Normal anti-collision algorithm. This scheme is used as the base value to evaluate the performance of the other three methods. Table 6.1 gives the simulation results for this algorithm.

2. Anti-collision with enhanced tag estimation. Table 6.2 lists the simulation results when the tag population is estimated using data extracted from the collision waveform.
3. Anti-collision with RN16 decoding using current protocol. Table 6.3 contains results for this algorithm in which RN16 decoding is used and one of the tag is correctly identified in a collision.
4. Anti-collision with RN16 decoding using modified protocol. Table 6.4 list the simulation results for the anti-collision algorithm which is a modified version of the ISO18000-6c protocol. This algorithm adds another command to the protocol which allows the reader to acknowldege more than one tag during one slot. On receipt of this command, a tag which sent its RN16 but did not receive a valid acknowledgement waits for the next slot. The remaining tags do not decrement their slot counters during this additional slot. This significantly boosts the efficiency of the algorithm.

Table 6.1. Results for Normal anti-collision algorithm (A)

Q value	Tags Identified	Actual Tags remaining	Estimated Tags Remaining
5	12	38	30
5	12	26	22
5	12	14	14
4	3	11	8
3	1	10	8
3	6	4	4
3	2	2	2
3	2	0	0

Table 6.2. Results for enhanced anti-collision algorithm (B)

Q value	Tags Identified	Actual Tags remaining	Estimated Tags Remaining
5	10	40	40
6	25	15	15
4	5	10	10
4	6	4	4
3	0	4	4
3	1	3	3
3	1	2	2
3	2	0	0

Table 6.3. Results for enhanced anti-collision algorithm (C)

Q value	Tags Identified	Actual Tags remaining	Estimated Tags Remaining
5	19	31	31
5	21	10	10
4	6	4	4
3	3	1	1
3	1	0	0

6.3 Hidden tag detection

Tags which are away from the reader have very low transmitted power levels. If one tag is near the reader antenna while another one is at some distance, the nearer tag will overshadow the distant one. Readers will correctly decode the nearer tag and will fail to detect the distant one.In one of our experiments, one tag was at 0.15m from the reader while another was at 1.3m. The reader software could correctly decode the nearer tag but failed to realize the presence of the second tag. Using our algorithm we were able to detect the presence of the distant tag in the RCS plot. This can be observed in Fig. 6.7 and Fig. 6.8

Table 6.4. Results for enhanced anti-collision algorithm (D)

Q value	Tags Identified	Actual Tags remaining	Estimated Tags Remaining
5	32	18	18
5	15	3	3
3	3	0	0

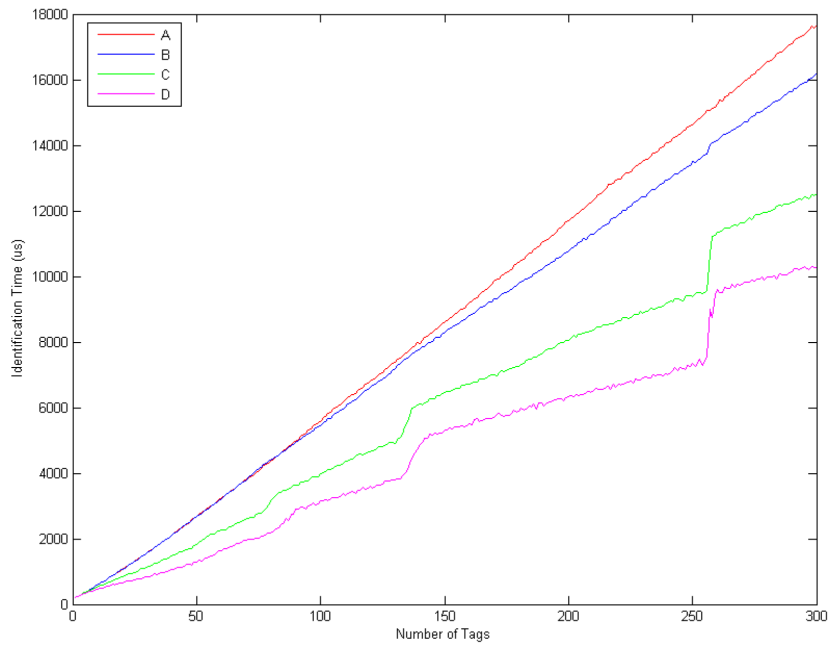

Figure 6.6. Performance comparison for the 4 algorithms.

6.4 Tag Random number generator evaluation

RFID systems use a dynamic frame slotted ALOHA anti-collision algorithm. Once the reader sets the frame size for that round, tags choose a slot number at random. This random number is generated by a random number generator on the tag. During evaluation of protocol performance, it is assumed that the random number generator output follows a uniform distribution function. This section analyses the impact on the identification process that a deviation from the uniform distribution

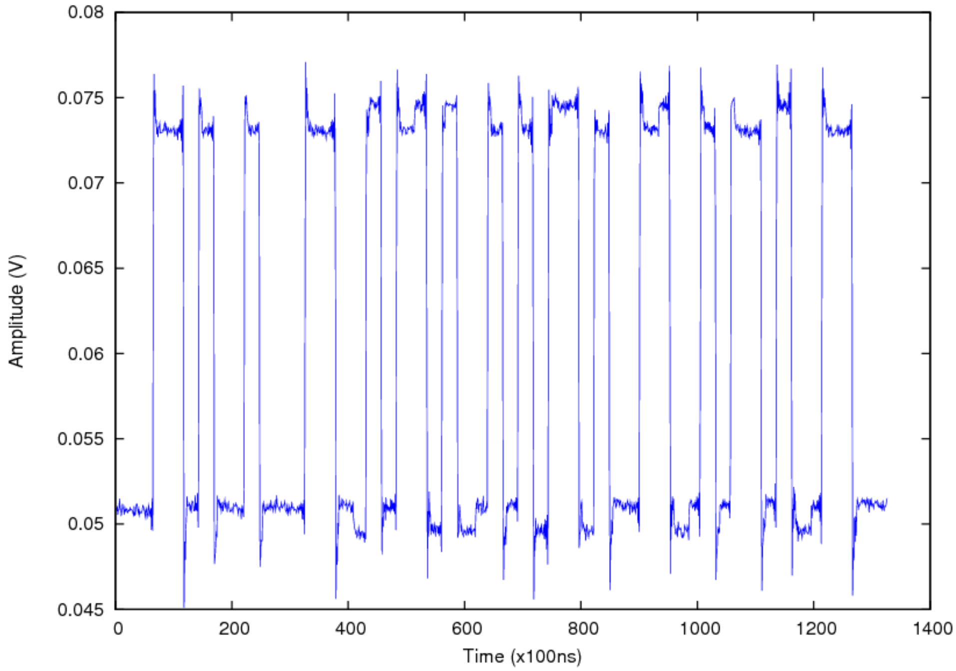

Figure 6.7. Strong and weak tag collision waveform.

may cause.

For this evaluation, three data sets of 10,000 readings each are generated. Each data set follows a Poisson distribution. Data sets A and B have the same value of λ while dataset C has a different value. Each data set represents a unique RFID tag. Tags A and B have the same RFID chip and thus follow the same distribution. A fixed Q value of 5 giving 32 slots is used in this analysis. Thus in each of the 10,000 rounds the data set has an integer value between 1 and 32 denoting the slot chosen by the tag. Fig. 6.9 shows the histogram for tags A and B with a λ value of 10 while Fig. 6.10 shows the histogram for tag C with a λ value of 15. Analysis of the data gives the following result:

Collisions when Tag A and B are in range = 898

Collisions when Tag A and C are in range = 442

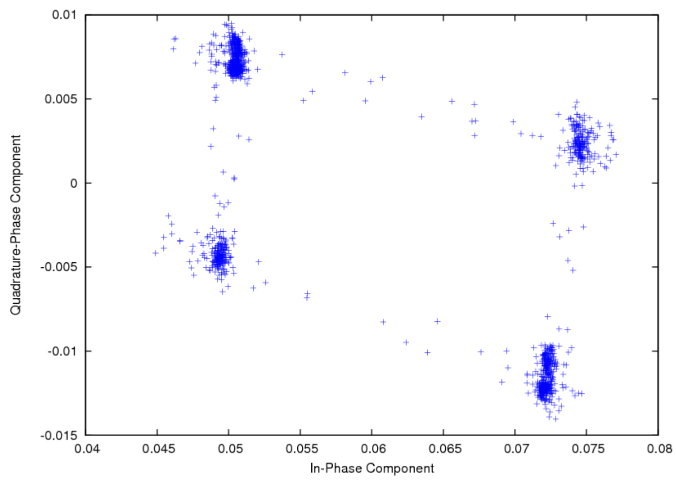

Figure 6.8. Strong and weak tag collision I-Q plot.

An experiment was carried out by using some standard RFID tags to find the distribution function of their random number generators. Pearson's chi-square test was carried out for all the 4 tags as well as a data set generated using a uniform pdf. The results are summarized in table 6.5

Table 6.5. Random number generator performance of common tags

Tag	Mean Square Error
bow-tie	41.43
excalibur	31.25
squiggle	22.53
TI	20.77
Reference data set	26.22

6.5 Effect of non-uniform PDF

Tag random number generators have a uniform distribution for the output values and they are distributed between 0 and 2^Q-1. In this section we analyze the

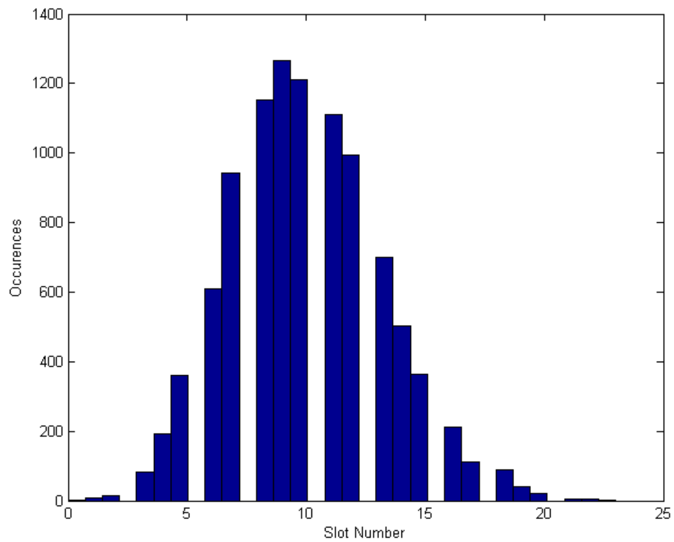

Figure 6.9. Random number distribution for tags A and B.

performance of the identification process if the random number generator has a probability distribution function like Gaussian, Poisson etc. Fig. 6.15 shows the various PDFs used and their distribution for a Q value of 6 which gives 64 slots.

Fig. 6.16 shows the identification time required for each of the above cases. We see that initially all approaches show similar identification times but when the number of tags in the field is 100 or more, Gaussian PDF shows an improvement over uniform PDF. The following values were used for the PDFs.

Uniform : range = 1 to 2^{Q}

Gaussian : mean = $2^{Q}/2$, variance = $2^{Q}/4$.

Poisson : $\lambda = 2^{Q}/2$

Rayleigh : $\sigma = 2^{Q}/4$

Gamma : a= $2^{Q}/4$, b = 2

For every alternate round only half the number of slots are used. This round is used

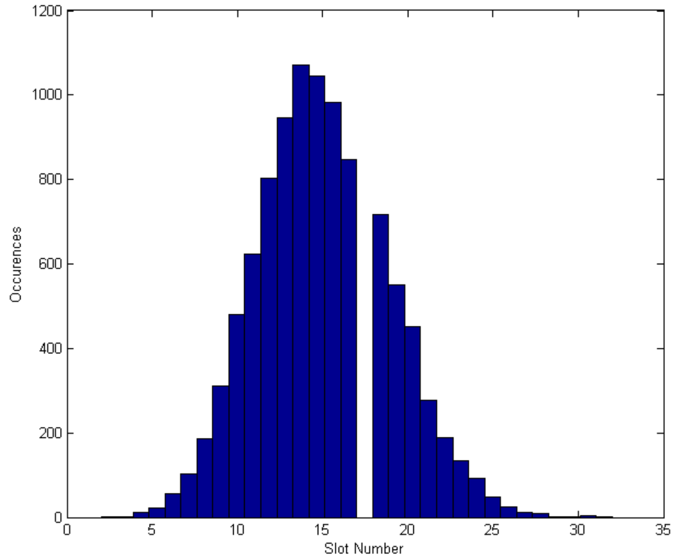

Figure 6.10. Random number distribution for tag C.

to then estimate the number of remaining tags in the field to decide the Q value for the next round.

A Gaussian PDF is defined by its mean and variance. For our simulation we keep the variance constant at $2^Q/4$. Fig. 6.17 shows the different Gaussian PDFs that were used in the simulation. Fig. 6.18 shows the results obtained from the simulation. We observe that there is not a significant difference in the identification time. However, when the Q value changes from 5 to 6(64 tags) and from 6 to 7(128 tags) and when the mean is less than $2^Q/2$, which is in the case of m=1/3 and m=1/4, performance decreases. This could be due to the fact that having the mean in the first half causes more collisions during estimation and gives a larger estimate than the true value of the number of tags remaining.

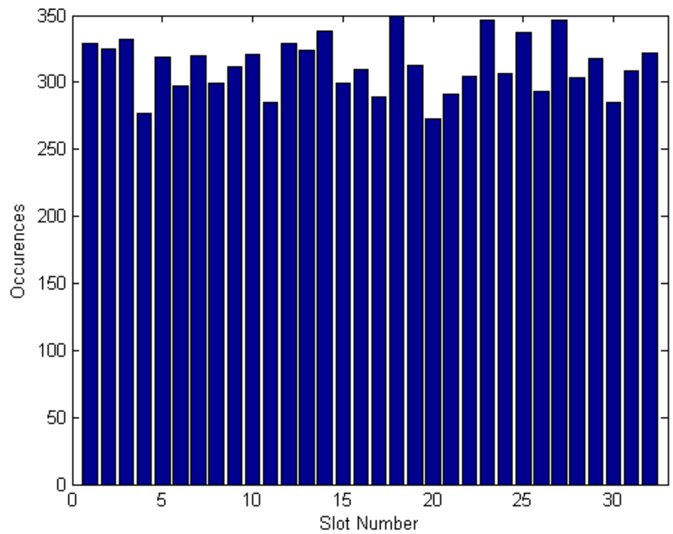

Figure 6.11. Bow-tie tag.

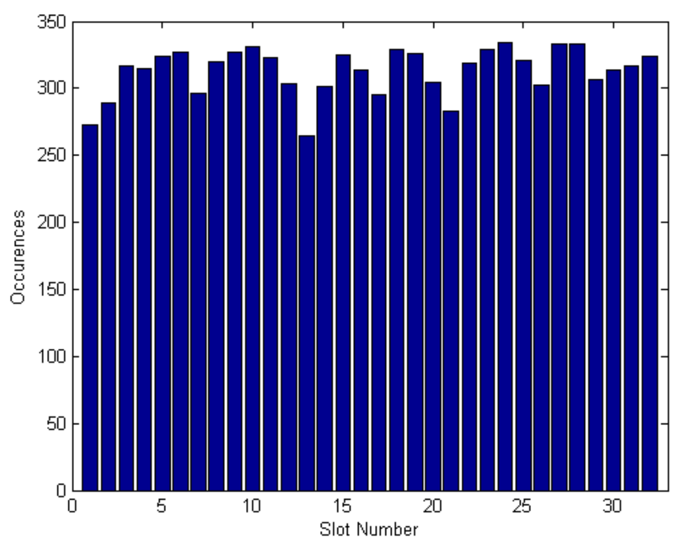

Figure 6.12. Excalibur tag.

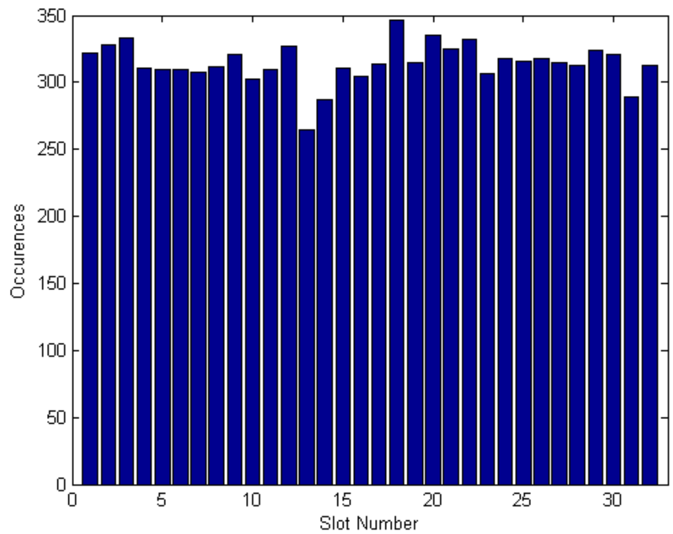

Figure 6.13. Squiggle tag.

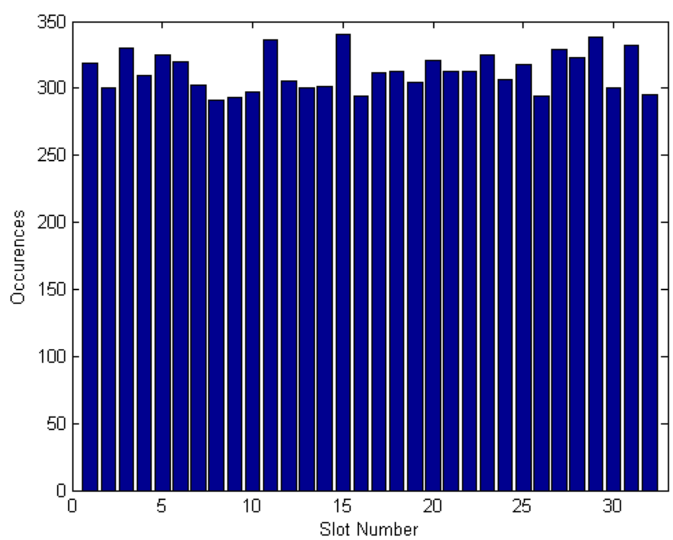

Figure 6.14. Texas instruments tag.

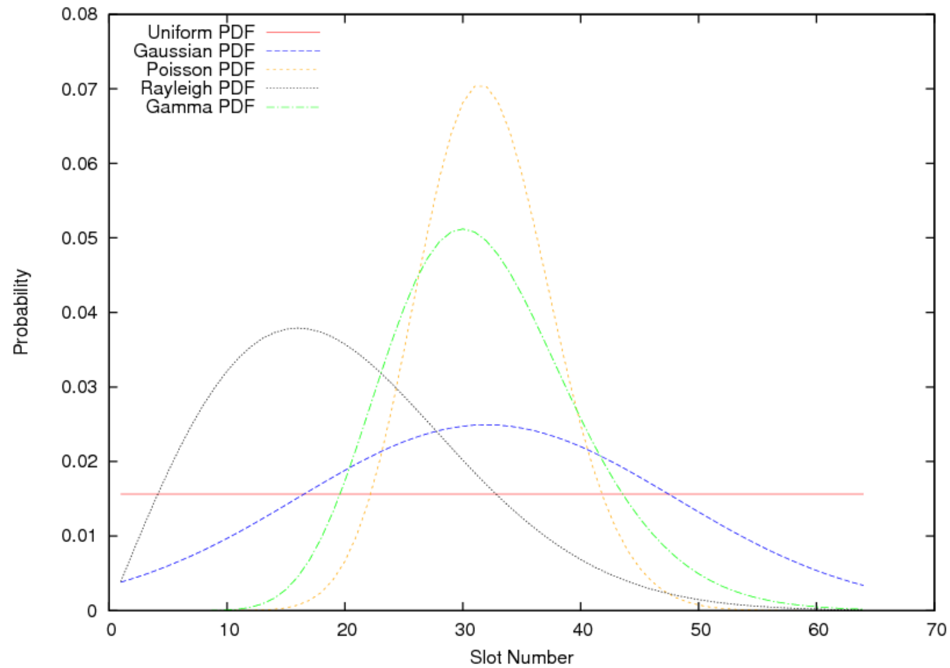

Figure 6.15. Probablity distribution functions used for simulation.

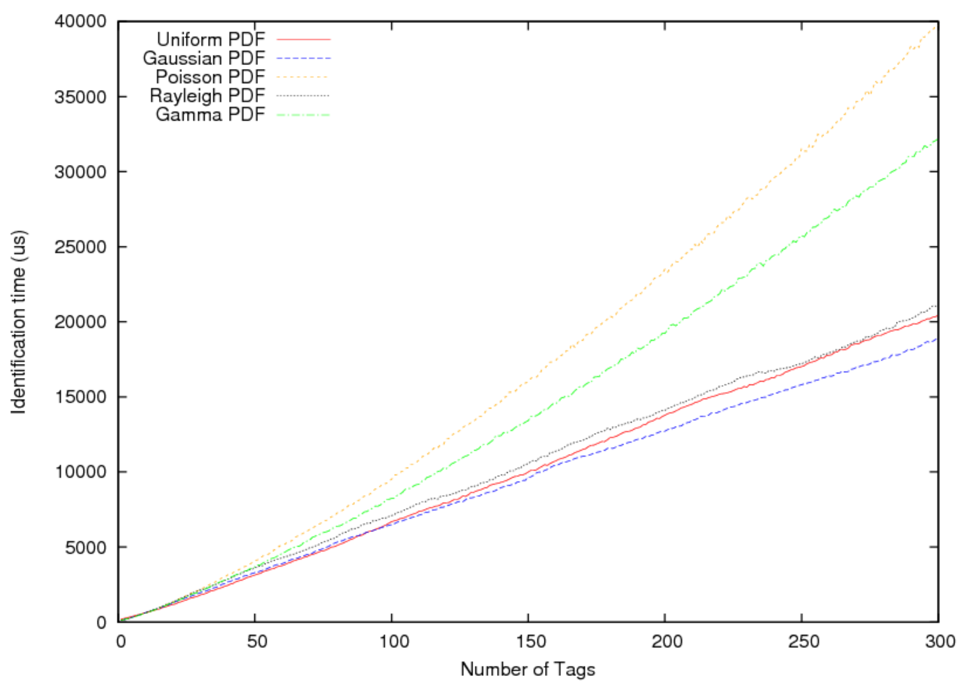

Figure 6.16. Performance using different PDFs.

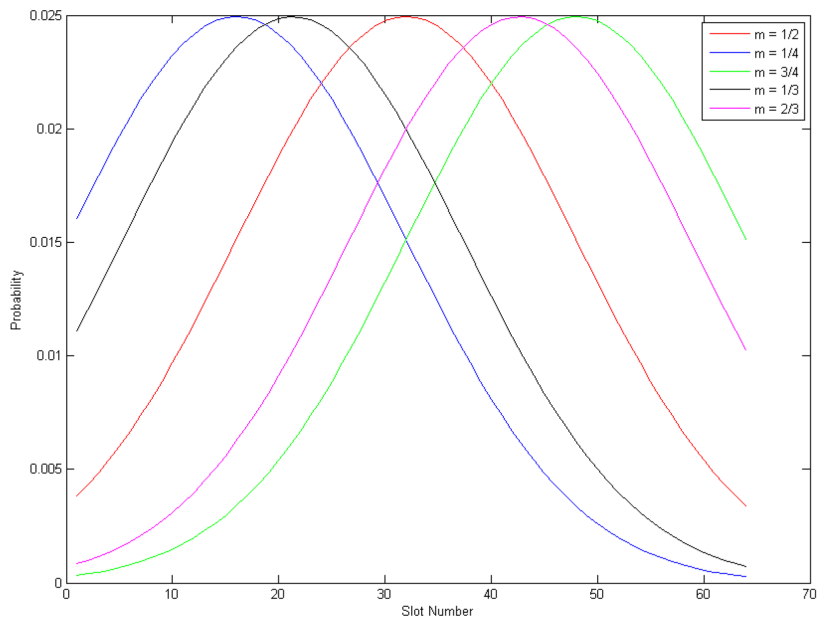

Figure 6.17. Gaussian PDFs used for simulation.

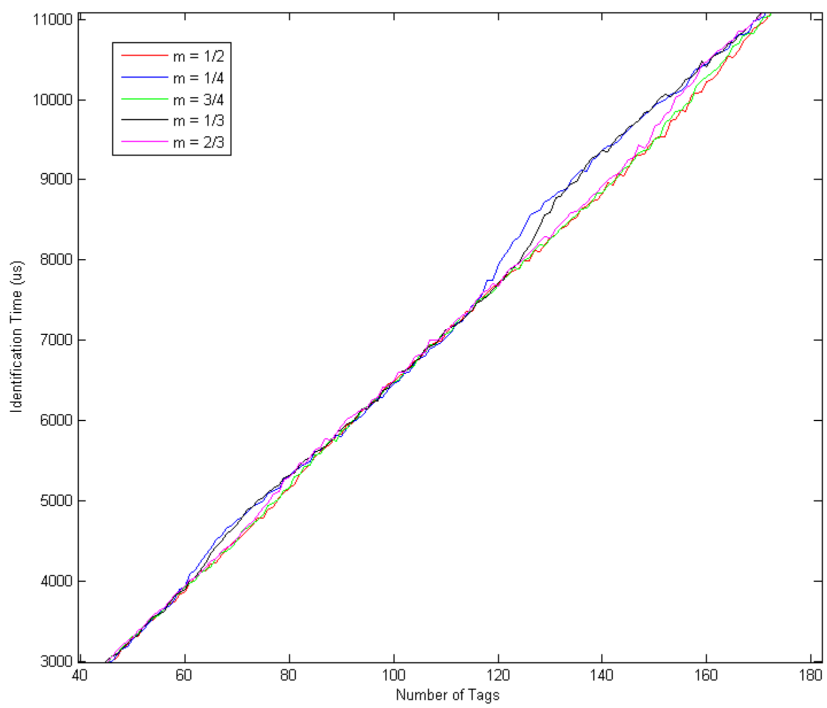

Figure 6.18. Performance using different Gaussian PDFs.

CHAPTER 7

USRP SYSTEM

A software-defined radio (SDR) system is a radio communication system which can tune to any frequency band and receive different modulation across a large frequency spectrum by means of a programmable hardware which is controlled by software. An SDR performs significant amounts of signal processing in a general purpose computer, or a reconfigurable piece of digital electronics. SDRs can provide the protocol engineer with wireless testbeds that are fully programmable at the DLC,MAC and PHY. The benefit of this flexibility highly depends on the performance and usability of the specific SDR.

7.1 Universal Software Radio Peripheral

The USRP consists of a motherboard containing upto four 12-bit, 64Msamples/sec ADCs, four 14-bit, 128M sample/sec DACs, a million gate, Field Programmable Gate Array (FPGA) and a programmable USB 2.0 controller. Each fully populated USRP motherboard supports four daughterboards, two for receiving and two for transmitting. RF front ends are implemented on the daughterboards.One USRP can simultaneously receive and transmit on two antennas in real time. All sampling clocks and local oscillators are fully coherent, thus allowing the creation of MIMO (multiple input, multiple output) systems. In the USRP, high sampling rate processing takes place in the FPGA, while lower sampling rate processing occurs in the host computer. The two onboard digital downconverters(DDCs) mix, filter, and decimate (from 64 M Samples/s) incoming signals in the FPGA. Two digital upcon-

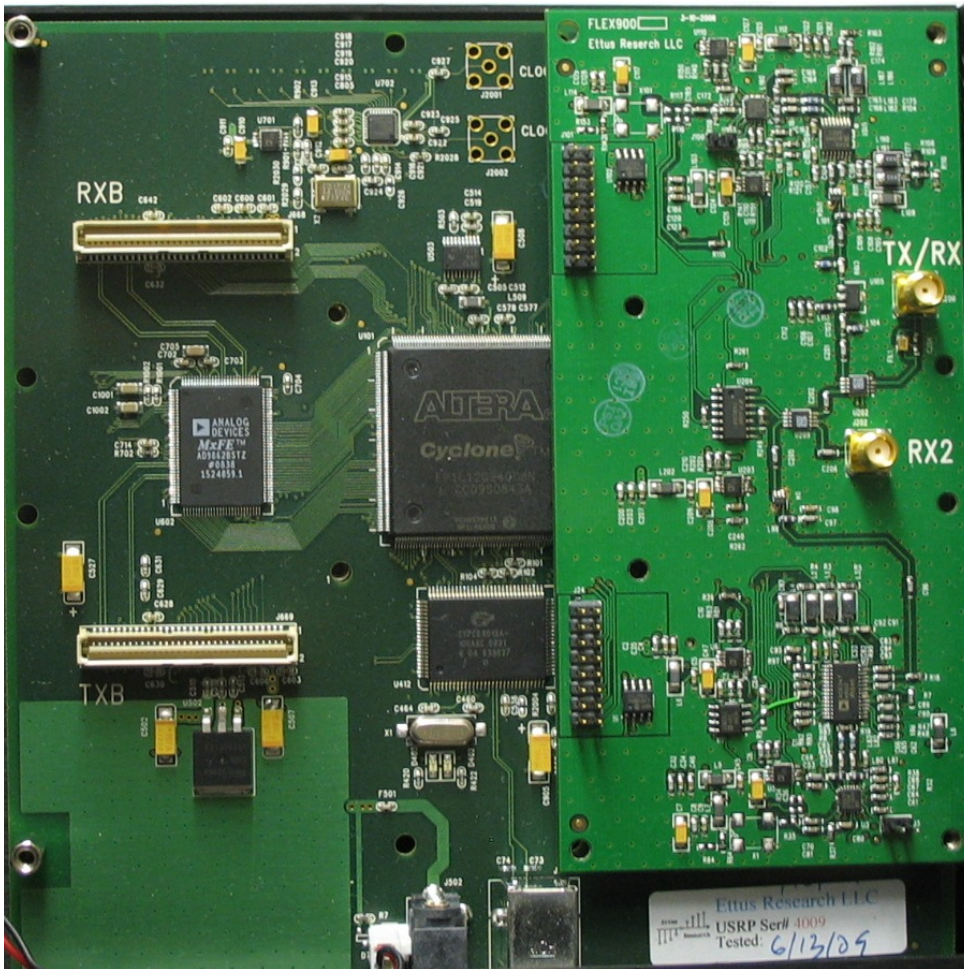

Figure 7.1. USRP motherboard with RFX900 transceiver.

verters (DUCs) interpolate baseband signals to 128 MS/s before translating them to the selected output frequency. The DDCs and DUCs combined with the high sampling rates also greatly simplify analog filtering requirements. Daughterboards mounted on the USRP provide flexible, fully integrated RF front-ends. The USRP accommodates up to two RF transceiver daughterboards (or two transmit and two receive) for RF I/O.

7.2 Software

GNU Radio is a free software development toolkit that provides the signal processing runtime and processing blocks to implement software radios using readily-available, low-cost external RF hardware and commodity processors. It is widely used in hobbyist, academic and commercial environments to support wireless communications research as well as to implement real-world radio systems.

Using GNU Radio, a radio can be built by creating a graph where the vertices are signal processing blocks and the edges represent the data flow between them. The signal processing blocks are implemented in C++ and the graphs are constructed and run in Python. Conceptually, a signal processing block processes an infinite stream of data flowing from its input ports to its output ports. A block's attributes include the number of input and output ports it has as well as the type of data that flows through each.

Some blocks have only output ports or input ports. Input and output ports serve as data sources and sinks in the graph. For instance, there are sources that read from a file or ADC, and sinks that write to a file, digital-to-analog converter (DAC) or graphical display. More than 100 blocks are currently implemented in GNU Radio. Using a generic RF front end and few other hardware components like the ADC and DAC, GNU Radio code implements software radio functionality to create a transceiver for AM, FM, BPSK, QAM and many other communication technologies.

7.3 UHF Reader using USRP

The USRP motherboard has many daughterboards available which can be used to provide the analog front end for that frequency range. As RFID systems use the 902-928MHz ISM we use the RFX900 transceiver. Specifications of RFX 900 are:

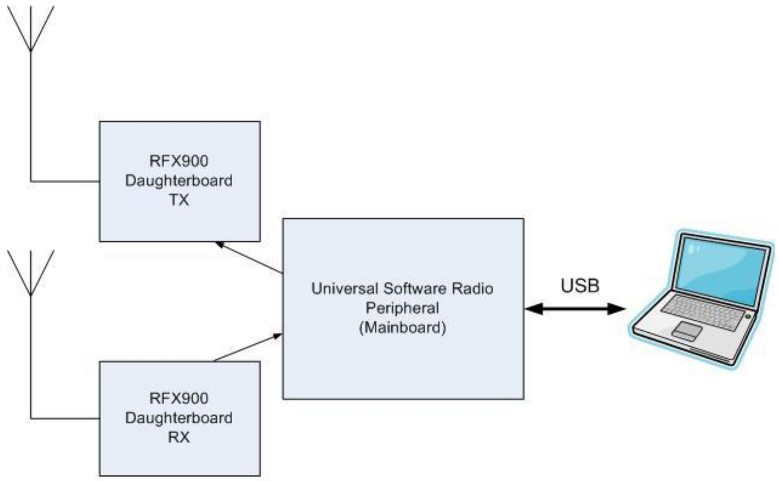

Figure 7.2. USRP and GNU Radio block diagram.

RX: 800MHz - 1000MHz

TX: 800MHz - 1000MHz @ 200+mW

The board features an ISM band filter that suppresses the RF signal outside the 902-928 MHz band and attenuates it within such band by one dB or two.

GNU Radio implements the baseband processing in software but the high speed FPGA on the USRP can be used to speed up time critical processing where the USB latency creates a problem.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

In this chapter we summarize the results of the research performed. This research focusses on improving the identification rate of present RFID systems. Physical layer collision signals were used for the same and changes in present algorithms are suggested.

8.1 Conclusions

Section 6.1 described the results of detecting the number of tags invloved in a collision using I-Q plot. Experimental results point out that in the 3 tag case, 71% accuracy was possible while for the 4 tag case 73% accuracy was possible .

Section 6.2 presented a simulation to find the theoretical performance increase using three different algorithms. The results are presented in table 8.1. Collision recovery by extracting the individual RN16s of the two tags involved in a collision can be used to convert a collided slot to a read slot. We do not know the expected RN16 values of the tags since they are randomly generated for each session. Our algorithm is used to recover the RN16s from the colliding signals. The only way to detect if the RN16 was correct is to send an ACK to the tags with the decoded RN16 and check if the tag responds. The EPC Class 1 Gen. 2 protocol allows only single ACK command to be sent. Even if we correctly decode both RN16s, we can acknowledge only one of the tags as the other tag will also receive this ACK and discard it as incorrect. This could be solved by adding a STACK command to the protocol which instructs tags involved in a collision to wait till the ACK command formed using their RN16 is received. These tags will not enter the arbitrate state when they receive ACKs meant for other tags.

Table 8.1 shows that the proposed algorithms show a 6.15%, 30% and 44.3% increase

Table 8.1. Performance of proposed algorithms

Algorithm	Average identification time (us)
A (Base)	8711
B	8175
C	6106
D	4853

in the identification efficiency. The low increase in efficiency in the first algorithm is partly due to the fixed frame sizes in the identification protocols. The latter two algorithms show a significant performance increase compared to the base algorithm. However this performance is expected to drop in practice due to the impact of accuracy in signal separation. Nonetheless, modification of the present protocol can be expected to give atleast another 10% performance benefit even by conservative estimates.

The method described in section 6.3 can successfully used to improve the reliability of an RFID reader. This ensures that none of the tags are missed in the identification process. This is of particular importance in application like store checkout with multiple items in a shopping cart.

The simulation in section 6.4 shows the impact of the random number generator on a tag which does not have a uniform distribution. The number of collisions when two tags of the same type are within range is significantly higher than the case when two different tags with different probability distribution functions are used. Experiments done on real world tags however suggest close similarity to the uniform probabilty distribution. Thus there is no significant rise in the number of collisions even if the same type of tag is used.

Section 6.5 analyzes the effect of non-uniform PDFs on the identification process. As the parameters of the distribution are known, every alternate round is partially completed and used for estimation. This shows an increased efficiency for 100 or more tags when a Gaussian PDF is used as compared to uniform PDF and other distributions. In the case of Gaussian PDF, efficiency is better when a mean of $2^Q/2$ and a variance of $2^Q/4$ is used. Shifting the mean does not give any performance benefit.

8.2 Future Work

The scalar RCS of a tag can be used to estimate the distance of the tags from the reader antenna. We have used the RCS plots for collision detection only. If the distance information is also used, collisions may then be avoided by a reduced carrier power level which avoids interference from the distant tag while allowing the nearer tag to be read.

A method for decoding RN16s from a two tag collision was proposed. This algorithm could be modified such that it may be used for RN16 recovery from a collision involving three or more tags.

The suggested collision detection and recovery algorithm should be implemented such that the processing time is less than the time limits mentioned in the ISO 18000-6c protocol specification. Software based radio boards like the Universal Software Radio Peripheral(USRP) described in chapter 7 can be used to implement the suggested algorithm on FPGA hardware. This will allow construction of an RFID reader with a higher tag identification rate.

APPENDIX A

SIMULATION CODE

This section contains the the MATLAB code that was used to run the simulations.

A.1 Inventory Round Simulation

A.1.1 Identification Time Plot

```
%Rushikesh Khasgiwale
%UTA E.E.
%Nov 2009
clc
clear all;
for i = 1:300
for j=1:100
t(j) = vogt1(i);
end
ident_time(i) = mean(t);
clear t;
end
plot(ident_time, 'r')
hold on
clear ident_time;
for i = 1:300
for j=1:100
t(j) = vogt2(i);
end
ident_time(i) = mean(t);
```

```
clear t;
end
plot(ident_time, 'b')
hold on
clear ident_time;
for i = 1:300
for j=1:100
t(j) = vogt3(i);
end
ident_time(i) = mean(t);
clear t;
end
plot(ident_time, 'g')
clear ident_time;
hold on
for i = 1:300
for j=1:100
t(j) = vogt4(i);
end
ident_time(i) = mean(t);
clear t;
end
plot(ident_time, 'm')
```

A.1.2 Algortihm A (Reference Algorithm)

```
%Rushikesh Khasgiwale
%UTA E.E.
%Nov 2009
function total = vogt1(n)
q=5;
slots = 2^q;
Tq = 10; %time for qry
Tread = 42;
Tempty = 5;
Tcoll = 18;
total=0;
while(n>0)
tag = unidrnd(slots,1,n);
[c0, c1, c2, ck] = count_coll(slots,n,tag);
t = Tq + (c0*Tempty) + (c1*Tread) + (ck*Tcoll);
n = n - c1;
nest = 2 * ck; %est remaining tags
q = getoptQ(nest);
slots = 2^q;
total = total+t;
end
```

A.1.3 Collision Detection

```
%Rushikesh Khasgiwale

%UTA E.E.

%Nov 2009

%Calculate collisions for this round

function [c0, c1, c2, ck] = count_coll(slots,n,tag)

%n = num of tags left

c0=0; c1=0; c2=0; ck=0;

for j = 1:slots

coll=0;

for k = 1:n

if(j==tag(k))

coll = coll + 1;

end

end

if(coll==0)

c0 = c0+1;

end

if(coll==1)

c1 = c1+1;

end

if(coll==2)

c2 = c2+1;

end

if(coll>2)

ck = ck+1;
```

```
end

end
```

A.2 Tag Random Number Generator Analysis

This section contains the code for simulating the performance of an RFID system in which the tag random number generator has a Gaussian probability distribution.

A.2.1 Identification Time Plot

```
%Rushikesh Khasgiwale
%UTA E.E.
%Nov 2009
%runs gaussian test for tags 1 to 300 tags in field
clc
clear all;
for i = 1:300
for j=1:100
t(j) = gauss(i);
end
ident_time(i) = mean(t);
clear t;
end
plot(ident_time, 'r')
```

A.2.2 Inventory Round Simulation

```
%Rushikesh Khasgiwale
%UTA E.E.
%Nov 2009
function total = gauss(n)
q=5;
slots = 2^q;
Tq = 10; %%time for qry
Tread = 42;
Tempty = 5;
Tcoll = 18;
u = slots/2;
sigma = slots/4;
total=0;
roundnum=1;
while(n>0)
tag = abs(round(normrnd(u,sigma,1,n)));
for p = 1:n %Fit values within 1:slots
if(tag(p)==0)
tag(p)=1;
end
if(tag(p)>slots)
tag(p)=slots;
end
end
if(mod(roundnum,2)==0)
```

```
[c0, c1, ck] = count_coll(slots,n,tag);

t = Tq + (c0*Tempty) + (c1*Tread) + (ck*Tcoll);

n = n - c1;

q = getoptQ(n);

else

[t,est_n, readslots] = predictngauss(tag,slots);

n = n - readslots;

q = getoptQ(est_n);

end

slots = 2^q;

u = slots/2;

sigma = slots/4;

total = total+t;

roundnum = roundnum +1;

end

end
```

A.2.3 Predicting Number of Tags

```
%Rushikesh Khasgiwale

%UTA E.E.

%Nov 2009

function [t,est_n,c1] = predictngauss(tag,slots)

u = slots/2;

sigma = slots/4;

Tq = 10; %time for qry

Tread = 42;

Tempty = 5;

Tcoll = 18;

c0=0;

c1=0;

ck=0;

readslots =0;

exp = hist(tag,u);

for l = 1:u

if(exp(l)==1)

c1 = c1 + 1;

end

if(exp(l)==0)

c0 = c0 + 1;

end

if(exp(l)>1)

ck = ck + 1;

end
```

```
end
x = 1:slots;
y = normpdf(x,u,sigma);
for i = 1:300
sum=0;
z = y .* i;
for j=1:u
sum = sum + (z(j) - exp(j))^2;
end
calc(i) = sum;
end
[c est_n] = min(calc);
est_n = est_n - readslots;
t = Tq + (c0*Tempty) + (c1*Tread) + (ck*Tcoll);
end
```

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BIOGRAPHICAL STATEMENT

Rushikesh Khasgiwale was born in Pune, India in 1984. He completed his Bachelors in Electronics and Telecommunication engineering from the University of Pune in 2005. He has two years of work experience as an embedded software engineer. Rushikesh's interest in research brought him to the University of Texas at Arlington in 2007 to begin graduate studies. He joined the Texas Radio Frequency Innovation and Technology Center where he conducts research on passive UHF RFID protocols. Rushikesh is currently a graduate teaching assistant in the Department of Electrical Engineering where he teaches digital systems and linear systems theory. His areas of interest include embedded systems, control systems and digital system design and integration.