# Performance evaluation of improved slotted ALOHA protocol

*A Project Report*

*submitted by*

**SHIKHAR SURYAVANSH**

*in partial fulfilment of the requirements*
*for the award of the degree of*

**BACHELOR OF TECHNOLOGY AND MASTER OF TECHNOLOGY**

**DEPARTMENT OF ELECTRICAL ENGINEERING**
**INDIAN INSTITUTE OF TECHNOLOGY MADRAS.**

**MAY 2018**

# THESIS CERTIFICATE

This is to certify that the thesis titled **Performance evaluation of improved slotted ALOHA protocol**, submitted by **Shikhar Suryavansh**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology and Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

**Dr. Srikrishna Bhashyam**
Research Guide
Professor
Dept. of Electrical Engineering
IIT-Madras, 600 036

Place: Chennai

Date: 10th May 2018

# ACKNOWLEDGEMENTS

I would like to expresses my greatest gratitude to my guide *Dr. Srikrishna Bhashyam* for his invaluable guidance, suggestions and continuous support during the course of my project work. This work would not have been possible without his incessant guidance and inspiration. I would like to thank all the faculty of the Electrical Engineering department of IIT Madras for their teaching and guidance during my various course works.

Research is an insurmountable task without the presence of peer support and guidance. In this regard, I would like to express my sincere gratitude to the team in the Wireless Communications and Information Theory lab for their support throughout this project. Working with the team has been an incredible learning curve for me.

I am grateful to my father *Mr. Akash Deep Pal*, my mother *Mrs. Sunita Pal* and my brother *Prakhar*, who have provided me moral and emotional support in my life. I also draw a special mention to *Kavya* for being my support system. I would also like to thank my friends *Akash, Dhruv, Junaid, Ketul, Manish, Ravi, Shivam, Shubham* and everyone else who has motivated me to work well.

# ABSTRACT

KEYWORDS: Random Access, Pure ALOHA, Slotted ALOHA, Diversity Slotted ALOHA, Contention Resolution Diversity Slotted ALOHA, Interference Cancellation, Packet Loss Ratio

Although the implementation of Demand Assignment Multiple Access (DAMA) Medium Access Control (MAC) protocol results in an efficient usage of the available bandwidth, Random Access (RA) schemes have always been a popular solution for wireless networks. ALOHAnet, now called Pure ALOHA, was the first such scheme used for wireless packet data network. Among the random access technologies, Slotted ALOHA (SA) has been widely used in satellite communication networks as initial access scheme. The last decade has seen a lot of improvements and enhancements in the SA protocol. The most popular among such enhancements are the Diversity slotted ALOHA (DSA) and Contention Resolution Diversity Slotted Aloha (CRDSA) schemes. DSA, as introduced in Choudhury and Rappaport (Mar. 1983), utilizes burst repetition of packets, leading to a better delay performance and lower Packet Loss Ratio (PLR) compared to the SA scheme at low normalized loads. A more efficient use of burst repetition is in CRDSA introduced in E. Casini and del Rio Herrero (Apr. 2007), which uses successive Interference Cancellation (IC) schemes to significantly improve the throughput, delay and PLR performances even under much higher normalized load conditions compared to DSA. In this work, we analyze the SA protocol and its improved versions (DSA and CRDSA) in detail and evaluate various performance measures of these schemes. We first perform simulations to affirm the existing results in the above mentioned works and then go on to perform new simulations to bring to light other important novel details about the performance of these schemes. We demonstrate the impact of various parameters on these performance measures and proceed to find out the ideal values of the parameters under the simulation conditions.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# ABBREVIATIONS

| | |
|---|---|
| **MAC** | Medium Access Control |
| **SA** | Slotted ALOHA |
| **DSA** | Diversity Slotted ALOHA |
| **CRDSA** | Content Resolution Diversity Slotted ALOHA |
| **IC** | Interference Cancellation |
| **SIC** | Successive Interference Cancellation |
| **RA** | Random Access |
| **PLR** | Packet Loss Ratio |
| **ST** | Satellite Terminals |
| **TDMA** | Time Division Multiple Access |
| **BPSK** | Binary Phase Shift Keying |
| **CRC** | Code Redundancy Check |
| **FEC** | Forward Error Correction |

# NOTATION

| | |
|---|---|
| $G$ | Rate of the transmission attempts, i.e., mean value of the Poisson distribution |
| $T$ | Round trip propagation delay |
| $\overline{R}$ | Average rescheduling delay for re-transmission |
| $k$ | Diversity order, i.e., number of copies of each packet |
| $\overline{D}_n$ | Normalized expected delay |
| $k_{av}$ | Average number of replications in probabilistic scheme |
| $N_{guard}^{RA}$ | TDMA slot guard expressed in symbols |
| $T_s$ | TDMA symbol duration |
| $M_{slots}^{RA}$ | Number of slots in each RA frame |
| $N_{slot}^{RA}$ | Number of symbols in each TDMA slot |
| $N_{frame}^{RA}$ | RA frame duration in terms of symbols |
| $\overline{s}[i,n]$ | Generic discrete burst signal samples array |
| $\overline{s}_{pre}[i]$ | Preamble sub-array of $\overline{s}[i,n]$ |
| $\overline{s}_{pay}[i,n]$ | Payload sub-array of $\overline{s}[i,n]$ |
| $\overline{s}_{guard}$ | Empty guard time sub-array of $\overline{s}[i,n]$ |
| $c_l[i]$ | $l-$th symbol of the preamble binary ($\pm 1$) BPSK modulated sequence |
| $d_{p,l}[i,n]$ | $l-$th in-phase binary ($\pm 1$) payload symbol |
| $d_{q,l}[i,n]$ | $l-$th quadrature binary ($\pm 1$) payload symbol |
| $\overline{r}[n]$ | Received signal samples |
| $N_{ST}$ | Total number of registered STs |
| $L[i,n]$ | Signal attenuation |
| $D[i,n]$ | Differential TDMA ST slot delay |
| $\phi[i,n]$ | Carrier phase offset |
| $\Delta w[i,n]$ | Frequency offset |
| $t[n]$ | Time corresponding to the start of slot $n$ |
| $\overline{w}[n]$ | Complex array representing a circular symmetric white Gaussian noise |
| $N_{iter}$ | Number of interference cancellation iterations in CRDSA demodulator |

# CHAPTER 1

# INTRODUCTION

The ALOHA protocol is a Random Access Protocol implemented on the Medium Access Control (MAC) layer that decides which one among multiple competing stations gets to access the multi-access channel next. Pure ALOHA and Slotted ALOHA (SA), the first variants of the ALOHA protocol were proposed more than 35 years ago. They differ mainly in the aspect that the time in pure ALOHA is continuous while it is discrete in slotted ALOHA. Ever since the introduction of SA, a lot of enhancements to the protocol have been proposed. The most important among them are the Diversity Slotted ALOHA (DSA) and Contention Resolution Diversity Slotted ALOHA (CRDSA) schemes which lead to improved performance compared to the classic SA protocol.

## 1.1 Pure ALOHA

ALOHAnet, also known as the ALOHA System and now known as **Pure ALOHA**, became operational in June 1971, resulting in the first public demonstration of a wireless packet data network. The primary usefulness of ALOHAnet was its use of a common shared medium for client transmissions. ALOHAnet's solution was to let each client send data whenever it had new data to send without any restrictions. To mark successful transmissions and deal with collisions, ALOHAnet had an acknowledgement/retransmission scheme. This method of data transmission significantly lowered the complexity of the protocol and networking hardware, since the client nodes do not need to interact with each other to negotiate who is allowed to send data. This solution became known as a pure ALOHA, or random-access channel, and was the basis for subsequent Ethernet development and later Wi-Fi networks.

## 1.2 Slotted ALOHA

**Slotted ALOHA (SA)** is a contention-based medium access scheme that is widely in use today. It was one of the earliest such schemes to be proposed. In a pure ALOHA system, a terminal can start transmission over a channel as soon as it has a ready packet to transmit. If a collision occurs, it waits for a random amount of time before re-transmitting. In contrast, there are discrete timeslots in the SA protocol and a terminal is allowed to transmit only at the beginning of a timeslot, thereby reducing the number of collisions and increasing the maximum throughput. The transmission is successful if and only if no other terminal attempts to use the channel during the same time slot. Collision occurs if multiple client nodes try to transmit in the same slot. In such case, all the collided packets need to be re-transmitted in the subsequent slots after waiting for a random number of slots. The major use of SA is in low-data-rate tactical satellite communications networks by military forces, in subscriber-based satellite communications networks, mobile telephony call setup, set-top box communications and in the contact-less RFID technologies.

## 1.3 Diversity Slotted ALOHA

Although SA offers the advantage that it requires little coordination among users, an average packet will have to be sent multiple times before success. This is because of the possible collisions that occur among packets at times. In satellite SA systems, this causes large packet delay. Hence, a generalization of SA random access scheme called **Diversity Slotted ALOHA (DSA)** has been introduced in Choudhury and Rappaport (Mar. 1983) wherein a user transmits a random number of copies of the same packet on a single high speed channel, at time instants spaced randomly (time diversity). It has been found that under the conditions of low traffic, the Diversity Slotted ALOHA (DSA) scheme gives better delay performance. Typically, when it is specified that the probability of a packet transmission failing a certain number of times should not exceed a time limit, a higher throughput can be obtained using multiple transmission. For satellite propagation systems with large round trip propagation delays, this is a reasonable requirement and hence, DSA has been considered for this.

## 1.4 Contention Resolution Diversity Slotted ALOHA

**Contention Resolution Diversity Slotted ALOHA (CRDSA)** is an improved version of the SA and DSA schemes and has much better throughput and delay performances for considerable traffic load. This schems has been introduced in E. Casini and del Rio Herrero (Apr. 2007). Similar to DSA, the users transmit multiple replications of packets in CRDSA as well. However, the most important and novel feature of CRDSA is that the collided packets can be resolved by using successive interference cancellation (SIC) techniques. In this way, CRDSA largely outperforms the classical SA and DSA schemes.

# CHAPTER 2

# Pure ALOHA

## 2.1 Introduction

The development of the ALOHA system began in 1968 by Norman Abramson and his colleagues at the University of Hawaii with an aim to connect several computers in the Hawaiian islands with a central computer located at the main Oahu campus using low-cost radio transmission equipment. In the pure ALOHA protocol, a station is allowed to transmit as soon as the packet to be sent is ready without checking if the channel is free. Since two or more stations might try to transmit packets at the same time instant, there is a possibility of collision of packets which would lead to the loss of the data packets. If a data packet is successfully transmitted, that is, no collision occurs, an acknowledgement is sent to the station.

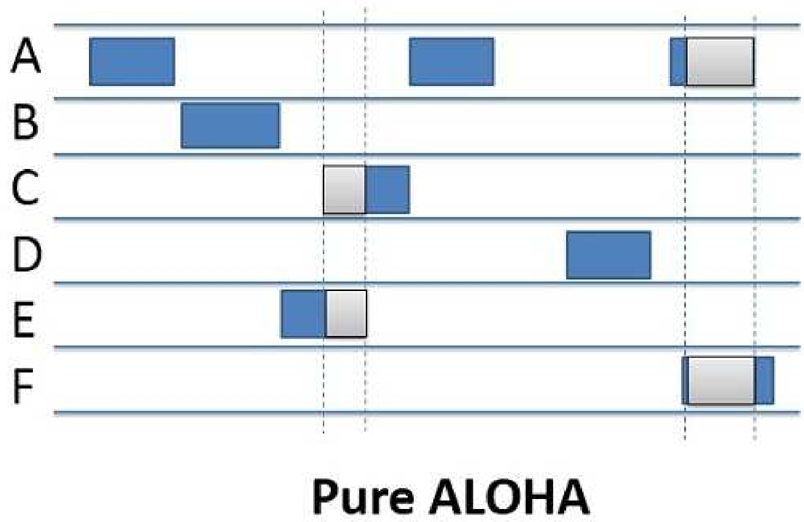


Figure 2.1: Pure ALOHA

Source: *Difference between pure and slotted ALOHA*

When there is a collision and the data frame is lost, the station re-transmits the data after waiting for a random time interval. The waiting time is made random so as to not let the same collisions repeat during re-transmission. Maximum throughput for pure ALOHA is obtained when all the data frames have the same length.

Since a transmitting station does not check whether the channel is free before it sends a data packet, the probability of collisions is very high and data needs to be re-transmitted. Due to this, the channel capacity is not used up to $100\%$. The time interval for which a station waits before re-transmitting affects the probability of a collision occurring and vice versa. These two factors determine the efficiency with which the channel is used. This implies that the efficiency of the protocol, the usage of channel capacity and the predictability of its behaviors are greatly affected by the back-off scheme employed.

The pure ALOHA protocol can be summarized as below:

- If there is a data packet to be sent, send it.
- If data from any other station is received while the data is being sent, it implies a collision has occurred and the data packet is "lost". In this case, wait for a random amount of time before re-transmitting the data packet.

## 2.2 System Model

The efficiency of a pure ALOHA scheme can be determined by estimating the rate at which frames are transmitted without collision, which is the throughput of the system. In order to simplify the estimation, the following assumptions are made:

- The frames are all of uniform length
- A frame cannot be generated by a station which is currently sending a frame or trying to transmit one.
- The number of stations that attempt to transmit follows a Poisson distribution. This includes the stations trying to send new frames as well as stations attempting to re-transmit lost frames.

Let "$T$" be the time it takes to transmit one data frame through the channel. Let a "frame-time" be defined as a time interval equal to $T$. In any given frame-time, let there be "$G$" number of stations trying to transmit on an average, i.e., the mean value of the Poisson distribution over transmission-attempt amounts. Thus, $G$ is the rate of the transmission-attempts.

For the successful transmission of a frame to occur, if a station starts transmitting at a given time instant, say "$t$", the remaining stations should not transmit till one time frame beginning at $t$. That is, the other stations should transmit only after the $(t + T)$th instant.

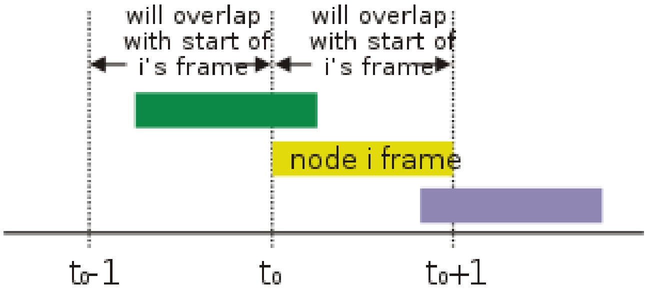


Figure 2.2: Overlapping frames in the pure ALOHA protocol. Frame-time is equal to 1 for all frames.

Source: *Wikipedia*

Since the number of transmission attempts in a single frame-time is Poisson distributed, the probability that there are $k$ stations trying to transmit in a particular time frame is:

$$Prob^{k}_{pure,1} = \frac{G^{k}e^{-G}}{k!} \tag{2.1}$$

The average amount of transmission-attempts for 2 consecutive frame-times is $2G$. Hence, the probability that there are $k$ stations trying to transmit in two consecutive frame-times is:

$$Prob^{k}_{pure,2} = \frac{2G^{k}e^{-2G}}{k!} \tag{2.2}$$

The probability that a transmission at time $t$ is successful is essentially the probability that zero transmissions occur in the time interval from $(t - T)$ to $(t + T)$. This can be found out by plugging in zero for the value of k in the equation (2.2). Hence, the probability $(Prob_{pure})$ of a successful transmission becomes :

$$Prob_{pure} = e^{-2G} \tag{2.3}$$

The throughput of the system is the rate at which successful transmissions occur which is equal to the product of the rate of transmission-attempts and the probability of a success. The throughput $(S_{pure})$ is given by:

$$S_{pure} = Ge^{-2G} \tag{2.4}$$

From the above equation, it is clear that the maximum possible throughput of the pure ALOHA system occurs when the value of $G$ is $0.5$. The throughput corresponding to $G = 0.5$ is $0.5/e$ frames per frame-time, which is approximately $0.184$ frames per frame-time. In other words, only about 18.4% of the total transmission time is used for successful transmissions in pure ALOHA.

## 2.3 Simulation results

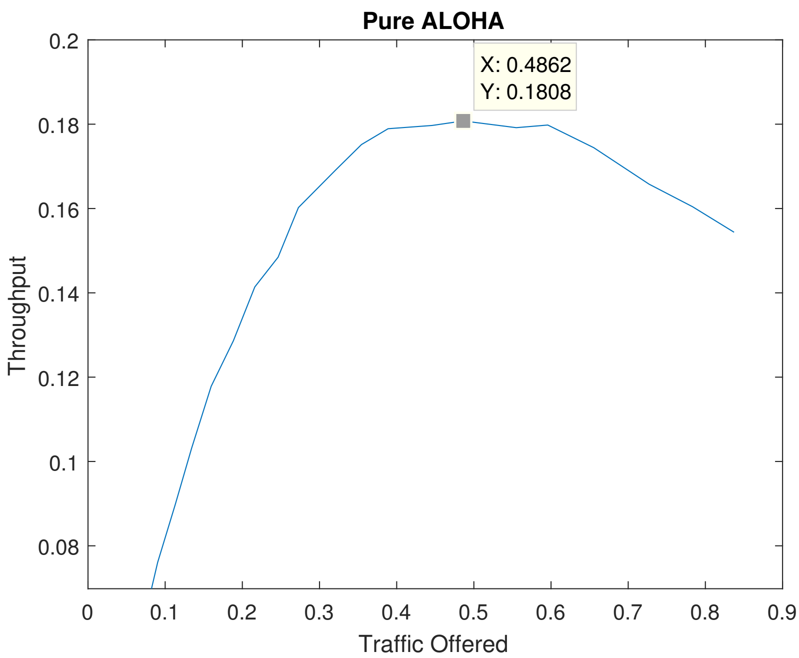


Figure 2.3: Plot of throughput vs traffic offered for Pure ALOHA protocol

Fig. (2.3) displays the simulation plot obtained by the implementation of Pure ALOHA protocol in MATLAB. The plot shows the variation of normalized throughput against the normalized traffic offered. As evident from the plot the throughput initially increases with the traffic offered, reaches a maximum value, and then decreases thereafter. When the offered traffic is very low, the resources are under-utilized meaning that most of the times the channel remains idle which results in lower throughput. A very high value of traffic offered would result in a lot of collisions and hence dropping and re-transmission of frames which again leads to lower throughput.

From Fig. (2.3), it is clear that maximum throughput for Pure ALOHA protocol is $18.08\%$ and is obtained at $G = 0.4862$ which is very close to the theoretical values derived in section (2.2).

Such a low value of maximum throughput in Pure ALOHA clearly indicates that it is a primitive protocol which does not use the resources efficiently which leads to a wastage of time. A significant improvement to Pure ALOHA is Slotted ALOHA which uses discrete timeslots for frames transfer and increases the maximum throughput.

# CHAPTER 3

# Slotted ALOHA

## 3.1 Introduction

The slotted ALOHA (SA) protocol was introduced in 1972 as an improvement to the pure ALOHA protocol. In the SA protocol, time is divided into discrete intervals, each equal to the length of a frame. Each of these discrete intervals is called a time slot. Slotted ALOHA does not allow the transmission of data whenever the station has the data to be send. A station is allowed to transmit only in the beginning of a time slot, as opposed to transmitting whenever there is a data frame ready to be sent in the pure ALOHA scheme. If a station "$misses$" a slot by not being able to place the data packet into the data channel in the beginning of a time slot it can only transmit in the beginning of the next time slot. When a collision occurs and the frame is lost, the station re-transmits in the beginning of a subsequent slot after waiting for a random amount of time.

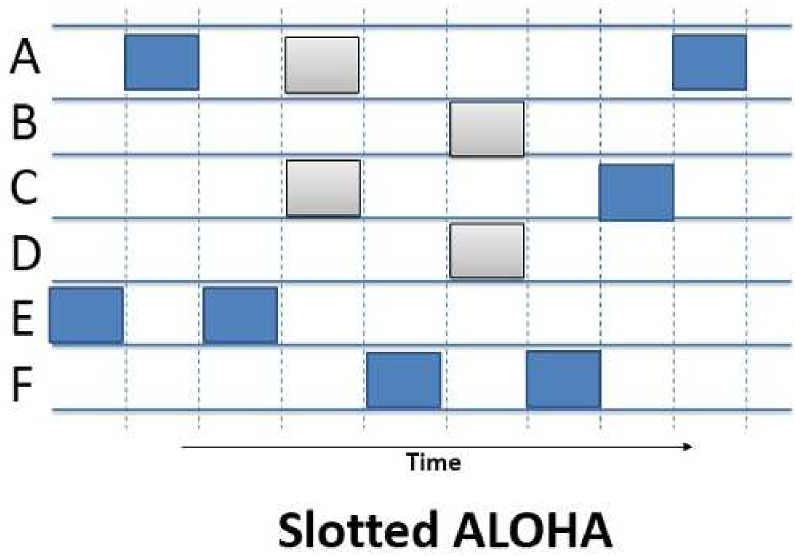


Figure 3.1: Slotted ALOHA

Source: *Difference between pure and slotted ALOHA*

Slotted ALOHA was proposed to increase the efficiency of pure ALOHA since the probability of collision in pure ALOHA is very high. The possibility of collisions still persists in slotted ALOHA and occurs when two different stations try to transmit in the beginning of the same time slot as shown in Fig. (3.1). The advantage with slotted ALOHA is that the chances of collisions are reduced to one-half as compared to pure ALOHA.

The procedure for slotted ALOHA can be summarized as below:

- If a data packet is ready to be transmitted at the beginning of a slot, send it. Otherwise, wait for the beginning of the next time slot to transmit.
- If a collision occurs, wait for a random amount of time and re-transmit in the beginning of the next slot.

## 3.2 System Model

The main assumptions made in the SA protocol are that all the nodes are synchronized and know when each slot begins, and if a collision occurs in a time slot, it is detected by all the stations before next time slot begins. Let "$G$" be the average number of attempts of transmission in a single timeslot (frame-time), that is, it is equal to the mean of the Poisson distribution governing the transmission-attempt amounts.

Unlike the previous case of pure ALOHA, here, we need to consider only one time slot (frame-time) and not 2 consecutive frame-times since collisions can occur only within a time slot. Therefore, the probability of no collisions taking place, or the probability that no other station attempts to transmit in the same time slot is given by:

$$Prob_{slotted} = e^{-G} \tag{3.1}$$

The probability that a frame takes exactly $k$ attempts to get successfully transmitted is obtained by multiplying the probability of one successful attempt and $k-1$ unsuccessful attempts as given by:

$$Prob^{k}_{slotted} = e^{-G}(1 - e^{-G})^{k-1} \tag{3.2}$$

The throughput can be calculated as the rate of transmission-attempts multiplied by the probability of success, and it can be concluded that the throughput $(S_{slotted})$ for slotted ALOHA protocol is:

$$S_{slotted} = Ge^{-G} \tag{3.3}$$

From the above equation it can be clearly seen that the maximum throughput occurs when $G$ is equal to $1$ and is equal to $1/e$ $(0.368)$ frames per time slot. This implies that in slotted ALOHA successful transmission occurs for $36.8\%$ of the total time.

## 3.3 Simulation results

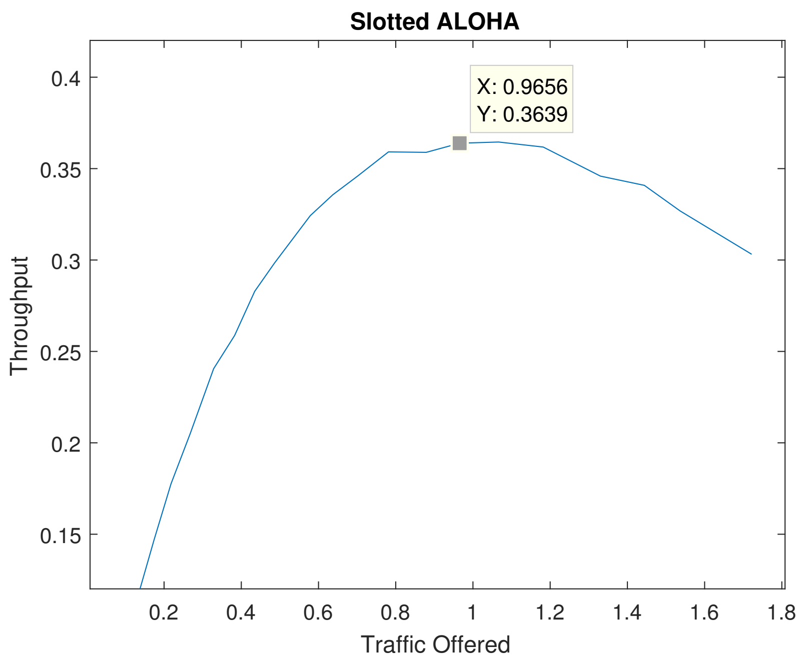


Figure 3.2: Plot of throughput vs traffic offered for Slotted ALOHA protocol

Fig (3.2) displays the simulation plot obtained by the implementation of Slotted ALOHA protocol in MATLAB. The plot shows the variation of normalized throughput against the normalized traffic offered per time slot. The plot has similar behavior as Pure ALOHA. However, as evident from the plot, the maximum throughput for slotted ALOHA protocol is 36.39% and is obtained at G = 0.9656 which is very close to the theoretical values derived in section (3.2).

Fig (3.3) shows the variation of mean delay against the normalized traffic offered.

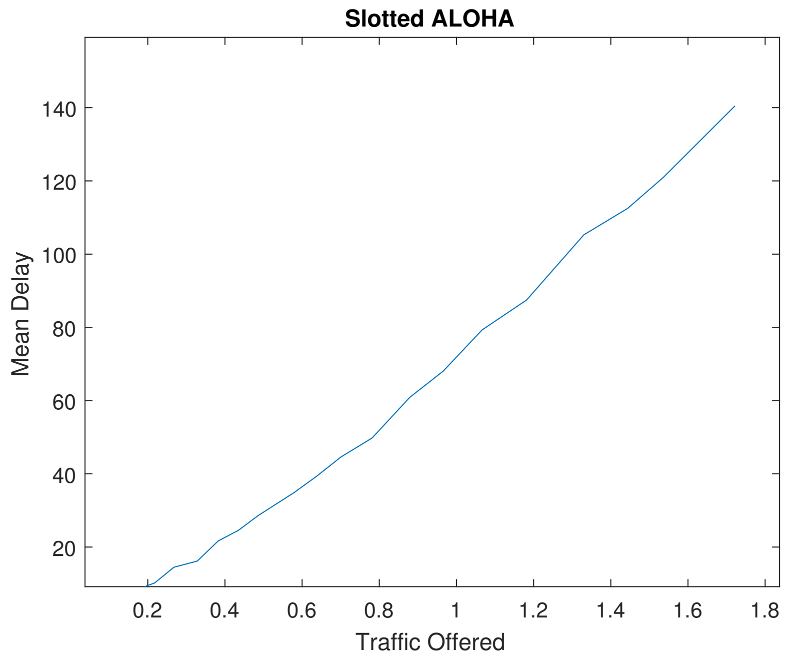


Figure 3.3: Plot of mean delay vs traffic offered for Slotted ALOHA protocol

Mean delay is the average delay measured in terms of number of slots for a frame to be successfully transmitted (acknowledged) from the moment it is ready at the source. As the offered traffic increases, more and more collisions and re-transmissions occur. Hence, the mean delay also increases. As evident from the Fig (3.3), this increase in the mean delay is almost linear with the increase in traffic offered.

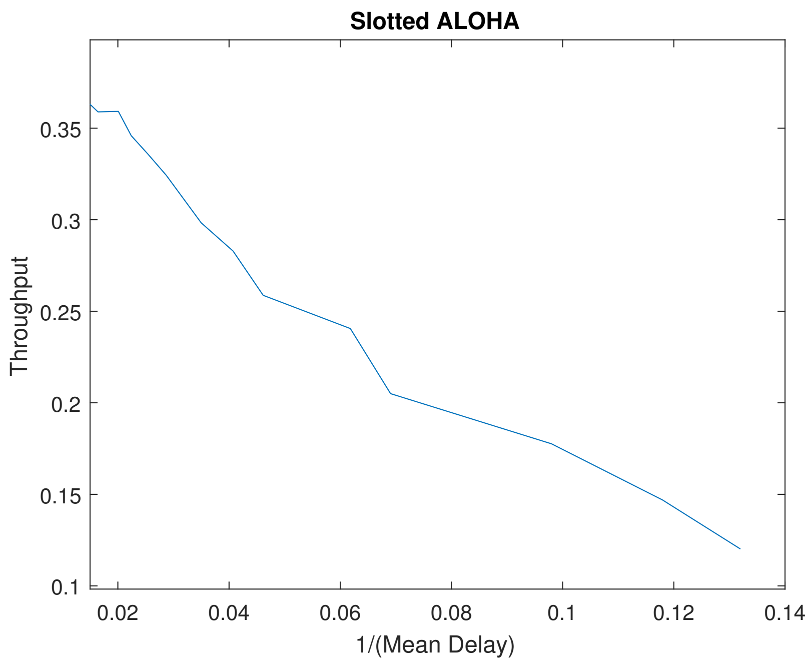


Figure 3.4: Plot of throughput vs 1/(mean delay) for Slotted ALOHA protocol

The maximum throughput occurs at G = 1 and is almost equal to 36%. However, the mean delay at G = 1 is equal to 70 slots. There is a clear trade-off between throughput and delay for $G < 1$. A higher throughput would result in a greater average delay.

Fig. (3.4) shows the throughput-delay trade-off. It shows the plot of throughput against 1/(mean delay). Lower values of delay would result in higher values of 1/(mean delay). As evident from Fig. (3.4), higher values of 1/(mean delay) would result in lower throughput and hence the trade-off.

## 3.4 Comparison of Pure and Slotted ALOHA

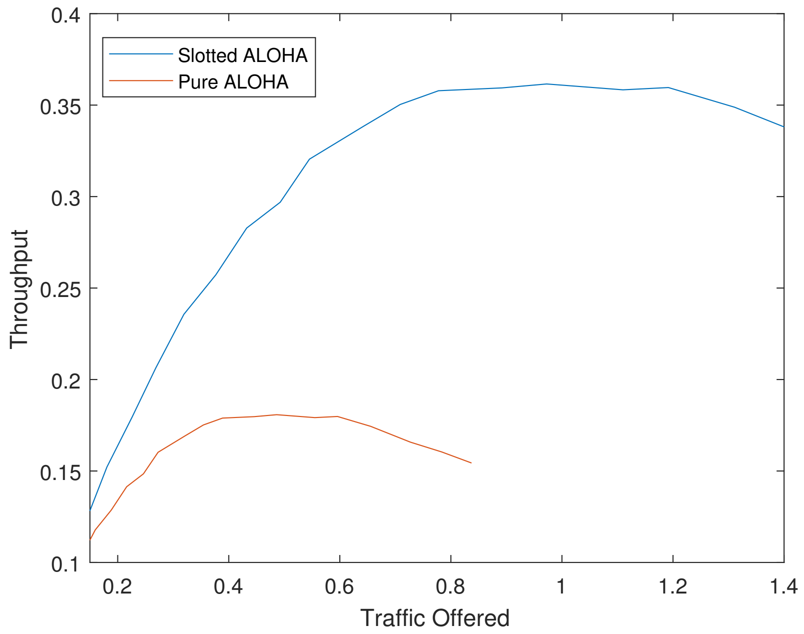


Figure 3.5: Plot of throughput vs traffic offered for Pure and Slotted ALOHA protocols

Fig. (3.5) shows the comparison of throughput vs traffic offered for pure and slotted ALOHA protocols. As evident from the figure, maximum throughput for slotted ALOHA ($\approx 36\%$) is almost double than that for pure ALOHA ($\approx 18\%$). Also, maximum throughput for slotted ALOHA occurs at G = 1 whereas for pure ALOHA occurs at G = 0.5.

The following comparison table lists the main differences between pure and slotted ALOHA protocols:

| Basis For Comparison | Pure ALOHA | Slotted ALOHA |
|---|---|---|
| Frame Transmission | The user can transmit the data frame whenever the station has the data to be transmitted. | The user has to wait till the next time slot start, to transmit the data frame. |
| Time | In Pure ALOHA the time is continuous. | In Slotted ALOHA the time is discrete. |
| Successful Transmission | The probability of successful transmission of the data frame is: $S = Ge^{-2G}$ | The probability of successful transmission of the data frame is: $S = Ge^{-G}$ |
| Throughput | The maximum throughput occurs at G = 1/2 which is 18%. | The maximum throughput occurs at G = 1 which is 36%. |

Table 3.1: Comparison of Pure and Slotted ALOHA protocols

# CHAPTER 4

# Diversity Slotted ALOHA

## 4.1 Introduction

Slotted ALOHA random access protocol has been into existence for a long time now and there have been a lot of attempts to improve the performance of normal slotted ALOHA. One such attempt deals with a generalization of slotted ALOHA called the Diversity slotted ALOHA (DSA) described by *G. L. Choudhury and S. S. Rappaport* in Choudhury and Rappaport (Mar. 1983) in which several copies of the same data packet are transmitted. The transmission is successful if any one of the multiple copies of the packet is correctly received. The paper describes two methods of transmitting multiple copies, namely, frequency diversity and time diversity. In frequency diversity, the multiple copies of the packet are transmitted on separate frequency channels at the same time. However, in time diversity the copies are transmitted spaced apart by arbitrary time intervals on the same channel. We will consider only time diversity here. Two different schemes within time diversity have been considered. In scheme 1, the number of multiple copies is fixed while it is random in scheme 2.

Diversity slotted ALOHA is most useful in satellite systems which have a large round trip propagation delay of about 270 ms. A striking feature of slotted ALOHA multiple access is that it requires negligible synchronization among users. However, due to frequent collision among packets in slotted ALOHA system, it is required on average that a packet be transmitted more than once before it can be correctly interpreted. This in turns leads to poor delay performance due to the large propagation delay. This is the motivation to transmit multiple copies simultaneously as the correct reception of any one of the copies would lead to huge savings in terms of delay performance.

In diversity slotted ALOHA, whenever a packet is generated by a user, $k$ copies of the same packet are transmitted. This number $k$ is called the diversity order of the scheme. If the receiver correctly interprets more than one copy of the same packet, then all except one of those copies are rejected. This is to ensure that the copies are not considered as discrete packets and it is assumed that some mechanism exists which allows the receiver to accomplish this task. In the section (4.2) of this chapter, the delay-throughput characteristics of the two time-diversity schemes have been considered. For each scheme, various orders of diversity $k$ have been taken into consideration to study the delay-throughput trade off.

## 4.2 Time Diversity

The multiple copies of the packet can be either simultaneously transmitted on different frequency channels or can be transmitted on a single high-speed channel at different time instants. The diversity scheme in which the multiple copies are transmitted on the same channel spaced apart by random time intervals is called time diversity. Two time diversity schemes have been considered here. The first scheme is a deterministic scheme employing a fixed number of copies ($k$) for each packet while the second is a probabilistic scheme employing a random number of copies for each packet.

## 4.3 Scheme 1 (Deterministic Packet Transmission)

### 4.3.1 System Model

In this scheme, a single high-speed satellite channel has been considered. Suppose $T$ and $\tau$ are the round trip propagation delay and the packet duration respectively. In most cases, $T$ is very large compared to $\tau$. Since the round trip propagation delay is $T$, a user waits for time $T$ after transmitting a packet to know whether the packet has been correctly received. In case of negative acknowledgement (incorrect reception), the user waits for a random rescheduling delay $R$ and then re-transmits the packet. For consecutive packet transmissions to be assumed independent of each other, it is required that the average rescheduling delay $\overline{R}$ be large (typically 5-10 times) compared to the packet duration $\tau$. For satellite systems, $\overline{R}$ is usually small compared to the round trip propagation delay $T$, although it is large compared to $\tau$.

The following transmission scheme has been taken into account: Each time a user has a new packet to transmit, he transmits $k$ copies of that packet $(k \geq 1)$ with each copy spaced by random rescheduling delays $R$. This is to ensure that the transmission of copies can be treated independent of each other as described above. Once all the $k$ replications have been transmitted, the user waits for any of them to be correctly received. If none of them is correctly received, the user re-transmits another $k$ copies after random rescheduling delay $R$. The spacing between these copies is also $R$.

The generation of packets by the user (both new and re-transmitted) has been assumed to be according to a Poisson process with rate $\Lambda$. On the average, the aggregate number of packets (new and re-transmitted) created per time slot has been defined as the total traffic $G$. As the process is Poisson, this implies that $G = \Lambda T$. Also, throughput $S$ has been defined as the amount of packets that are correctly received (successful transmission) per time slot.

As previously mentioned, $k$ copies are transmitted for each packet. As the transmission of the copies is independent, it can be assumed that the transmission of replicas is also Poisson with rate $\Lambda k$. Thus, the average number of packet copies generated per time slot is $\Lambda k \tau = kG$ and the probability that a particular transmitted copy succeeds is given by

$$P'_S = exp(-kG) \tag{4.1}$$

The probability that at least one of the $k$ replications of a packet will be successful is given by

$$P_S = 1 - (1 - P'_S)^k \tag{4.2}$$

The throughput is then

$$S = GP_S \tag{4.3}$$

Let us now look at the derivation of an analytical expression for the delay considered in the paper. The delay $D$ has been defined as the time difference between the transmission and successful reception of a packet. In general, it may be required that a packet be transmitted a lot of times before it is correctly received. In each such transmission, $k$ copies of the packet will be transmitted. The delay $D$ takes into account the time difference between the transmission of the first replication of the packet in the first attempt and the time at which the user is certain that the packet has been successfully transmitted. As far as delay $D$ is considered, only the first success for a packet is considered. It might so happen that more than one copies of the packet are successfully received, however, only the first success is taken into consideration. The expected delay is represented by $\overline{D}$.

The following events may occur during the first attempt of packet transmission by the user.

$Event\ 1$ : In this case, we assume that at least one copy of the packet transmitted in the first attempt is correctly received. Let this copy be the $m$th one, where $1 \leq m \leq k$. The occurrence of this event has a probability equal to $(1 - P'_S)^{m-1}P'_S$ and given this even has occurred, the excepted delay is equal to $T + (m-1)\overline{R}$.

$Event\ 2$ : In this event, it is assumed that none of the copies in the first attempt succeed. In such a scenario, the user will re-transmit $k$ copies after a delay $R$. The probability of none of the copies succeeding in the first attempt is $(1 - P'_S)^k$. In case of occurrence of this event, the user will know after an expected time $T + (k-1)\overline{R}$ that none of the replications in the first attempt succeeded. During the second attempt after a random time $R$, the probability of success is uninfluenced by the result of the first attempt and hence, the expected remaining delay remains the same, i.e., $\overline{D}$ at the beginning of the second attempt as well. So, in case of event 2, the total expected delay would be $T + (k-1)\overline{R} + \overline{R} + \overline{D}$.

During the first attempt, either event 1 or event 2 can only occur. Therefore,

$$\overline{D} = \sum_{m=1}^{k} (1 - P'_S)^{m-1} P'_S [T + (m-1)\overline{R}] + (1 - P'_S)^k [T + (k-1)\overline{R} + \overline{R} + \overline{D}]$$

Some algebraic manipulations result in the following:

$$\overline{D} = \frac{T}{1-(1-P_S')^k} + \frac{\overline{R}(1-P_S')}{P_S'} \tag{4.4}$$

The normalized delay is obtained as following after normalizing with respect to the round trip propagation delay $T$,

$$\overline{D}_n = \frac{1}{1-(1-P_S')^k} + \frac{(\overline{R}/T)(1-P_S')}{P_S'} \tag{4.5}$$

### 4.3.2 Existing simulation results

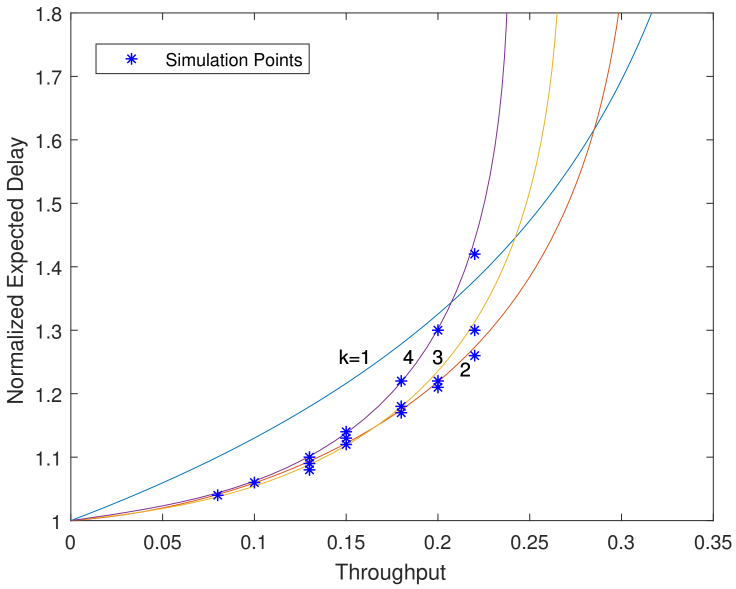


Figure 4.1: Throughput-normalized expected delay trade-off. Time diversity, scheme 1, $\overline{R}/T = 0.1$, various k.

The delay throughput curves as shown in Fig. (4.1) and (4.2) have been simulated to reproduce the results obtained in Choudhury and Rappaport (Mar. 1983). Using equations (4.1)-(4.5), the throughput $S$ and the corresponding delay $\overline{D}_n$ can be determined. In Fig. (4.1) and (4.2), $\overline{D}_n$ has been plotted as a function of $S$ for various values of the ratio $\overline{R}/T$ and $k$. Fig (4.1) also shows the simulation points. The number of users is assumed to be 100 and the round trip propagation delay $T$ is taken to be equal to 100 slots for the simulation. It can be inferred from Fig. (4.1) and (4.2) that, for light traffic, the diversity schemes ($k > 1$) clearly outperform the normal slotted ALOHA ($k = 1$) scheme in terms of the delay performance. However, for heavy traffic, the $k = 1$ scheme has a lower delay compared to the other diversity orders and hence performs better. The

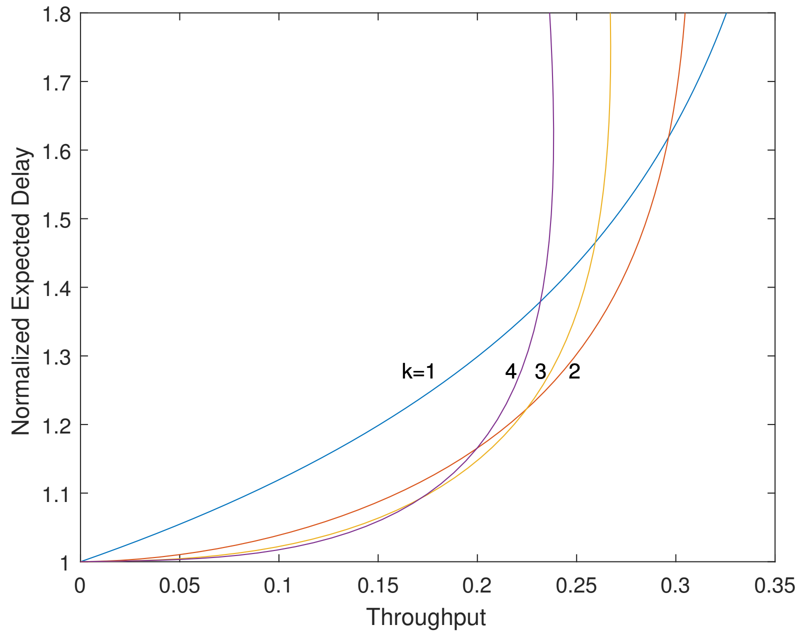


Figure 4.2: Throughput-normalized expected delay trade-off. Time diversity, scheme 1, $\overline{R}/T = 0.01$, various k.

$k > 1$ schemes have almost similar performance for light traffic but vary significantly as the traffic increases with $k = 2$ performing better than the other ($k > 1$) schemes at heavy traffic. On the whole, it is evident that $k = 2$ scheme is the strongest as it gives good delay performance over a wide range of input traffic. Also, a closer look at the Fig. (4.1) and (4.2) explains the impact of $\overline{R}/T$ ratio on the delay performance of the schemes. It can be observed that under light input traffic condition, the $k > 1$ schemes perform better for a lower value of $\overline{R}/T$ ratio.

### 4.3.3 New simulations results and conclusions

With a motivation from the reproduction of results obtained in Choudhury and Rappaport (Mar. 1983), a couple of new simulations were performed and results obtained in order to bring into consideration certain other important characteristics pertaining to diversity slotted ALOHA. Fig (4.3) shows the plot of Packet Loss Ratio (PLR) versus input traffic for different values of diversity order $k$. As expected, for any given $k$, the PLR increases with an increase in traffic because of higher number of collisions. For light traffic ($G < 0.18$), the diversity schemes ($k > 1$) perform better than the normal slotted ALOHA ($k = 1$) scheme as the PLR is higher for $k = 1$ scheme. The PLR for ($k > 1$) schemes is lower and almost similar to each other under light traffic conditions. How-

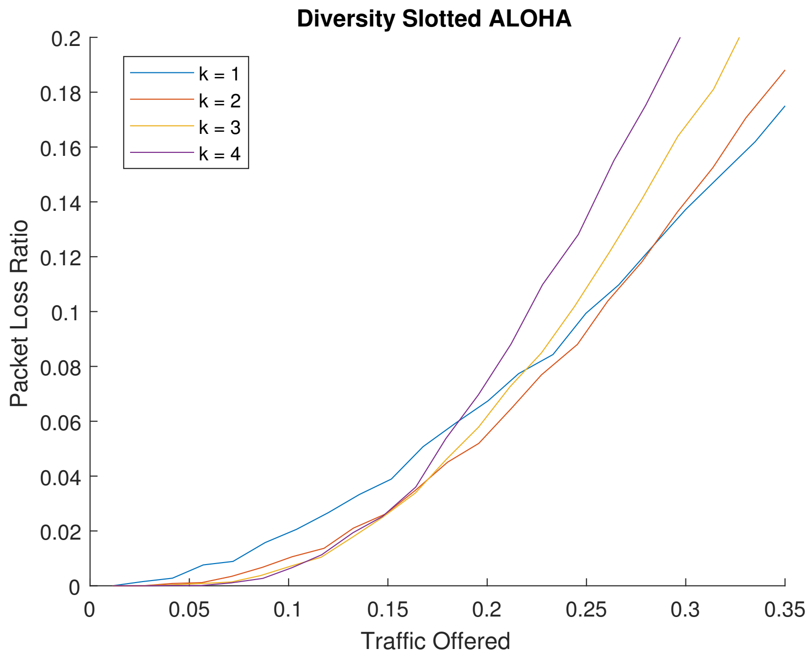


Figure 4.3: Plot of Packet Loss Ratio vs Traffic Offered, various k.

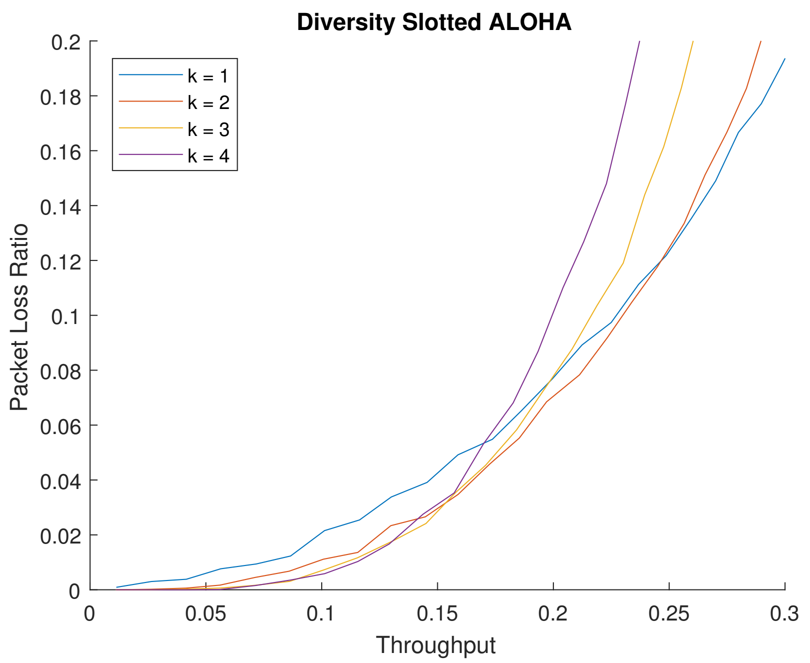


Figure 4.4: Plot of Packet Loss Ratio vs Throughput, various k.

ever, for heavy traffic, the performance of the diversity schemes vary significantly with $k = 1$ producing the lowest PLR. The results obtained can be intuitively explained as following: Under low traffic, the probability of collisions is low and hence the diversity schemes ($k > 1$) lead to lower PLR as the correct reception of any one replication of a packet is considered a success. However, under high traffic, the probability of collisions become very high and more replications ($k > 1$) lead to greater collisions and hence poorer performance (higher PLR). Although, if proper interference cancellation (IC) techniques are employed, then the diversity schemes ($k > 1$) would lead to a better performance under much higher traffic conditions also, as interference cancellation would lead to more packets being successfully received. This will be discussed in the next chapter under Contention Resolution Diversity Slotted ALOHA (CRDSA). Fig (4.4) shows the plot of Packet Loss Ratio versus Throughput for different diversity orders $k$. The nature of this plot and its explanation is the same as that for PLR vs traffic offered as described above.

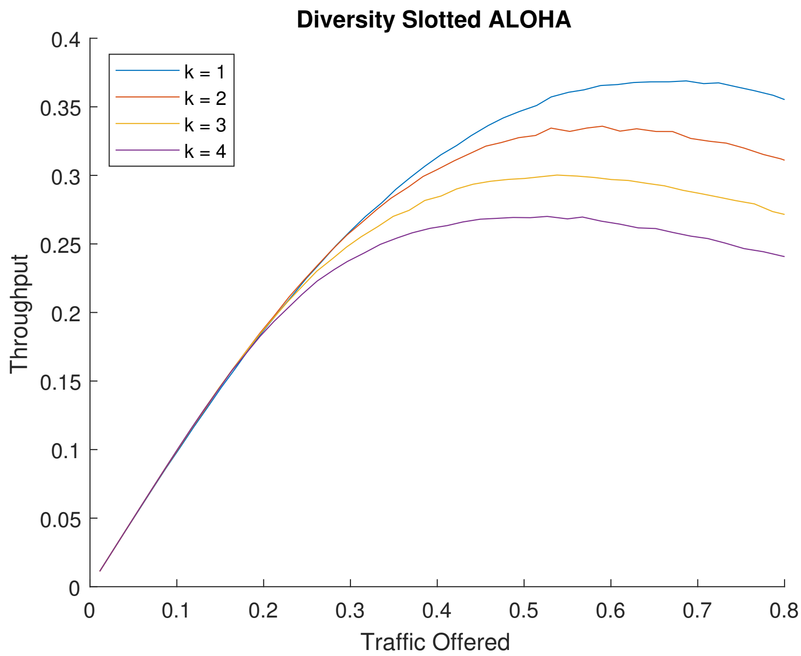


Figure 4.5: Plot of Throughput vs Traffic Offered, various k.

Fig (4.5) shows the plot of throughput versus traffic offered for different values of the diversity order $k$. As evident from the plot, for light traffic, the variation of throughput with traffic offered is almost the same for all the diversity schemes. However, for heavy traffic, $k = 1$ scheme provides the best throughput performance and the performance reduces as $k$ increases.

## 4.4 Scheme 2 (Probabilistic Packet Transmission)

### 4.4.1 System Model

Unlike scheme 1 where the number of replications were fixed, scheme 2 is a probabilistic scheme in which the user transmits a random number of replications of the packet. For simplicity we confine ourselves to the case $k = 2$, i.e., after transmitting the first replication of the packet, the user may not necessarily transmit the second packet. The second packet is transmitted with a probability $p$. It is evident that for for $p = 0$ and $1$, this probabilistic scheme corresponds to the deterministic scheme $1$ with $k = 1$ and $2$, respectively.

During each attempt of the user, the probability of transmitting one replication is $(1 - p)$ and the probability of transmitting two replications is $p$. Hence, during each attempt, the average number of replications transmitted is

$$k_{av} = 2p + (1 - p) = 1 + p \tag{4.6}$$

The generation of packets by the user has been assumed to be according to a Poisson process with rate $\Lambda$. Since the successive transmissions of replications are assumed to be independent of each other, it implies that the transmission of replications also follow a Poisson process with rate $\Lambda k_{av} = \Lambda(1 + p)$. Thus, the channel traffic is given by $\Lambda(1 + p)\tau = G(1 + p)$ (where $G = \Lambda\tau$) and the probability of success of a copy transmitted on the channel is

$$P'_S = exp[-G(1 + p)] \tag{4.7}$$

In each attempt, the user will either send one or two replications. Let $P_S$ represent the probability that a packet succeeds in a particular attempt. This would happen if at least one replication of the packet succeeds. The probability of success will be $P'_S$ if the user decides to transmit only one copy of the packet. However, if the user decides to transmit two copies, the probability of success will be $1 - (1 - P'_S)^2$. Hence, the probability of packet success is $P_S = (1 - p)P'_S + p[1 - (1 - P'_S)^2]$ or

$$P_S = (1+p)P'_S - p(P'_S)^2 \tag{4.8}$$

The throughput $S$ is given by

$$S = GP_S \tag{4.9}$$

The expression for the expected delay $\overline{D}$ can then be determined as shown below. The following events may occur during the first attempt of the user to transmit a packet.

$Event\ 1$ : In this event, we assume that the user decides to transmit only one replication and it succeeds. The probability of occurrence of this event is $P'_S$ and the expected delay in this case is $T$.

$Event\ 2$ : In this event, we assume that the user decides to transmit only one replication and it fails. The probability of occurrence of this event is $(1-p)(1-P'_S)$ and the expected delay, given this event has occurred is $T+\overline{R}+\overline{D}$.

$Event\ 3$ : In this event, the user decides to transmit two replications such that the first replication fails, and the second replication succeeds. The probability of occurrence of this event is $p(1-P'_S)P'_S$ and the expected delay, given this event has occurred is $T+\overline{R}$.

$Event\ 4$ : In this event, the user decides to transmit two replications and both the replications fail. The probability of occurrence of this event is $p(1-P'_S)^2$ and the expected delay, given this event has occurred, is $T+\overline{R}+\overline{R}+\overline{D}$. Since these are all the possible events, the expected delay is given by

$$\begin{aligned}\overline{D} &= P'_S T + (1-p)(1-P'_S)[T+\overline{R}+\overline{D}] \\ &\quad + p(1-P'_S)P'_S[T+\overline{R}] + p(1-P'_S)^2[T+\overline{R}+\overline{R}+\overline{D}]\end{aligned}$$

After some algebraic manipulations and normalization with respect to $T$, we get the normalized expected delay as

$$\overline{D}_n = \frac{1}{P'_S[1 + p(1 - P'_S)]} + \frac{(\overline{R}/T)(1 - P'_S)}{P'_S} \tag{4.10}$$

### 4.4.2 Simulation results and conclusions

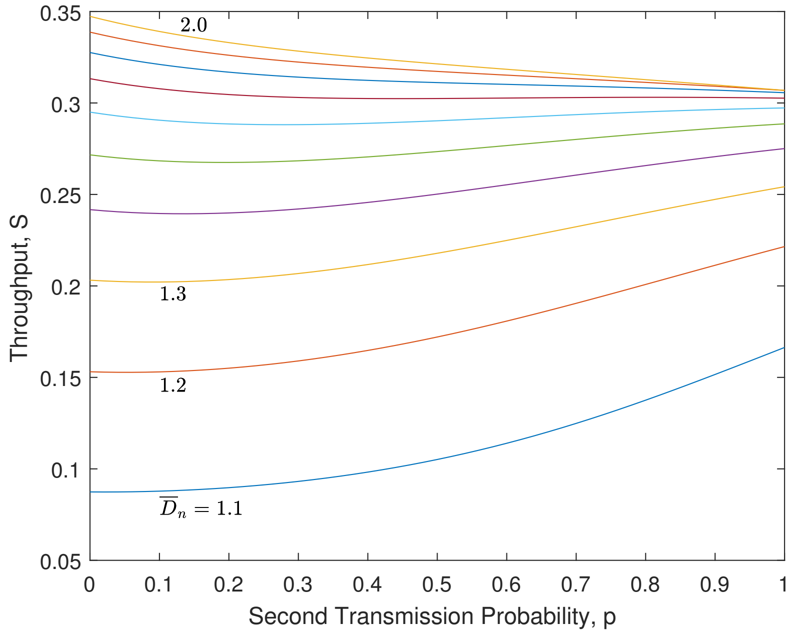


Figure 4.6: Throughput $S$ as a function of second transmission probability $p$ for specified normalized expected delay $\overline{D}_n$. Time diversity, scheme 2, $\overline{R}/T = 0.01$, various $\overline{D}_n$.

Using equations (4.7)-(4.10), the throughput $S$ can be determined for any specified normalized expected delay $\overline{D}_n$. For a given value $\overline{D}_n$, $S$ will be a function of $p$ and $p$ should be chosen such that it maximizes the throughput $S$. Fig. (4.3) shows the plot of $S$ versus $p$ for different specified normalized delays $\overline{D}_n$ and with $\overline{R}/T = 0.01$. As evident from the plot, for any value of $\overline{D}_n$, the maximum throughput always occurs at one of the endpoints of the curve, i.e, either at $p = 0$ or at $p = 1$. We know that the endpoints, i.e., $p = 0$ and $1$, correspond to the deterministic scheme $1$ with $k = 1$ and $2$, respectively. This implies that for $\overline{R}/T = 0.01$, the deterministic policy is always better than probabilistic policy. The same conclusion has been obtained for a wide range of values of $\overline{R}/T$.

Fig (4.7) and (4.8) have been obtained for $\overline{R}/T$ equal to $0.1$ and $0.001$, respectively. As evident from Fig (4.7) and (4.8), the same conclusion that the deterministic policy is always better than the probabilistic policy holds true.

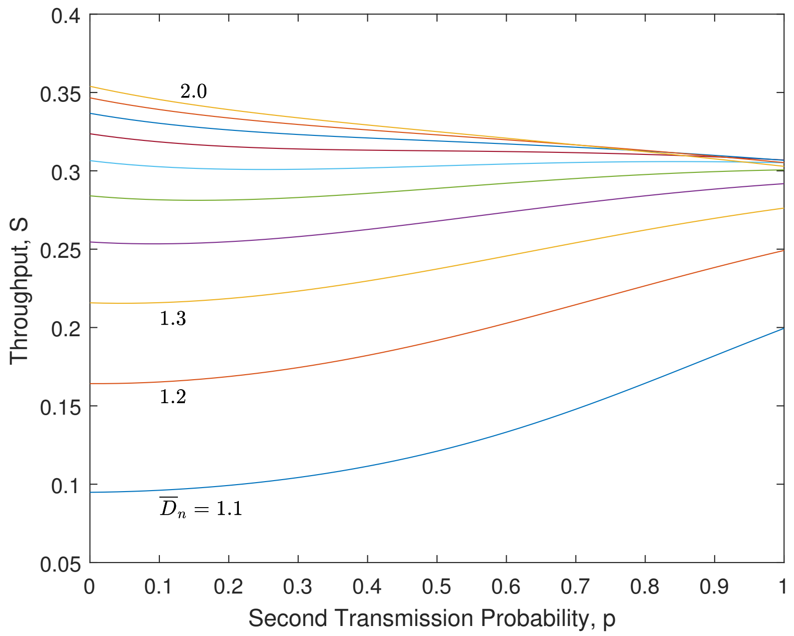


Figure 4.7: Throughput $S$ as a function of second transmission probability $p$ for specified normalized expected delay $\overline{D}_n$. Time diversity, scheme 2, $\overline{R}/T = 0.1$, various $\overline{D}_n$.

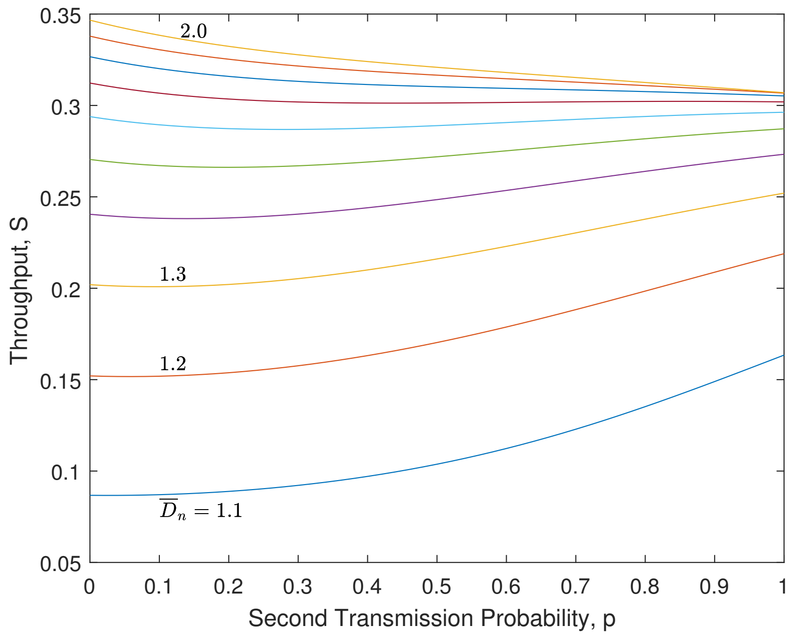


Figure 4.8: Throughput $S$ as a function of second transmission probability $p$ for specified normalized expected delay $\overline{D}_n$. Time diversity, scheme 2, $\overline{R}/T = 0.001$, various $\overline{D}_n$.

# CHAPTER 5

# Contention Resolution Diversity Slotted ALOHA

## 5.1 Introduction

Contention Resolution Diversity Slotted ALOHA (CRDSA) is a superior version of Diversity Slotted ALOHA (DSA) which incorporates efficient Interference Cancellation (IC) techniques along with the diversity transmission of data bursts as described in E. Casini and del Rio Herrero (Apr. 2007). It has been demonstrated that under similar packet loss ratio conditions, CRDSA performs a lot better than normal slotted ALOHA (SA). CRDSA makes random access (RA) very competent and results in low latency for the transmission of small-sized sporadic packets as it allows to supplement the performance of RA channels in the incoming link of interactive satellite networks. Similar to DSA, the CRDSA protocol also generates multiple replicas of the same packet (called the diversity order $k$) at random times within a frame instead of generating just one packet as in SA. E. Casini and del Rio Herrero (Apr. 2007) considers the case of only two replicas per packet. However, later in this chapter, we have also considered the case of more number of replications per packet and illustrated the impact of diversity order in the performance of CRDSA. The most important feature of CRDSA is the utilization of efficient Interference Cancellation (IC) techniques which helps in resolving most of the DSA packet collisions. While DSA marginally improves the SA performance by augmenting the probability of successful packet transmission at the cost of increased RA load, CRDSA significantly improves the throughput performance by resolving most of the frame packet contentions using IC techniques which relies on the frame composition information from the replica bursts. CRDSA not only results in a much better operational throughput than SA and DSA, but also leads to improved packet loss ratio and reduced packet delivery delay under similar traffic conditions.

## 5.2 System Assumptions

As stated in Section 5.1, the return link of a satellite access network (i.e. link from satellite terminal to the gateway) has been considered. Satellite networks appear to be the most natural implementation of the CRDSA scheme though the application of the scheme is not only restricted to such networks. A bent-pipe satellite payload has been assumed in which there is one gateway providing the ground network access and all the users are connected to it through the satellite. In this case, the inbound link demodulator is considered to be located on-board the satellite. The inbound resources according to the selected access scheme is shared among the discrete Satellite Terminals (ST). It is assumed that the STs will manage the TDMA slot synchronization once registered in the network. The slot timing error is assumed to be bounded by $\tau_{max} = N_{guard}^{RA} T_s$, where $N_{guard}^{RA}$ represents the TDMA slot guard expressed in symbols, $T_s$ is the TDMA symbol duration and $R_s = 1/T_s$ is the ST baud rate. Optionally, the STs transmitted power can be restrained by a power control mechanism based on a closed loop method.

## 5.3 Random Access Scheme

The TDMA frame structure proposed in E. Casini and del Rio Herrero (Apr. 2007) for the RA scheme is shown in Fig. 5.1.

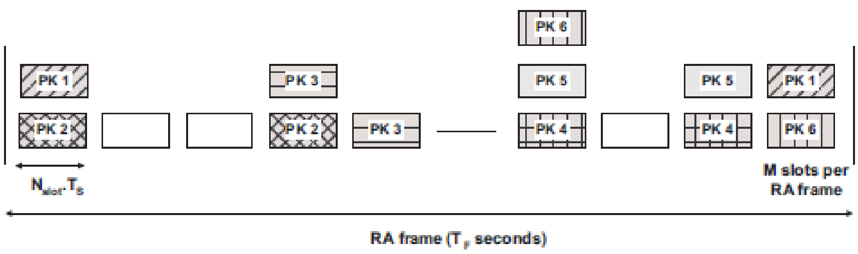


Figure 5.1: TDMA frame structure for the Random Access channel.

Source: E. Casini and del Rio Herrero (Apr. 2007)

There are $M_{slots}^{RA}$ in each RA frame. At most one MAC packet can be transmitted per RA frame by one satellite terminal. The terminal physically sends two replications of the same packet (called "twins" bursts) in two randomly selected slots within the same frame (see Fig. (5.1)). The two copies have absolutely same preamble and payload information bits. The pay load of each copy also contains signalling information bits which has information regarding the slot position of the corresponding twin burst in the frame. Each replica contains pointer to its twin and vice versa. We know from DSA that transmitting the same packet two times improves the probability of successful transmission to some extent for small loads. However, the key innovation of CRDSA lies in the fact that the retrieved information from a successful replication of a packet can be used to cancel out the interference that may have been caused by its twin in another slot in the frame. Iteration of this approach multiple times can be used to recover most of the frames that were initially lost due to collision(s). The example provided in Fig. (5.1) can be used to explain the above process. In Fig. (5.1), packet 2 cannot be initially recovered as both the copies of the packet have undergone a collision. In slot 1, a copy of packet 2 suffered a collision with one of the copies of packet 1 while in slot 4, the twin copy of packet 2 collided with one of the copies of packet 3. However, in slot 5, the other copy of packet 3 suffered no collision and can be successfully recovered. This information can now be used to cancel out the interference caused by packet 3 in slot 4. Thus, after removing the interference caused by packet 3, packet 2 can be recovered in slot 4. In the next iteration, packet 1 can also be recovered from slot 1 after removing the interference generated by packet 2 so that packet 6 can be subsequently recovered in slot $M$. This heuristic explanation clearly illustrates the crucial role of IC along with DSA and twin location signalling for efficient interference resolution in CRDSA.

### 5.3.1 RA Channel Description

As previously described, each RA frame is composed of a fixed number of slots $M_{slots}^{RA}$. Each TDMA slot is of duration $N_{slot}^{RA}$ symbols and can allocate one RA burst. Each RA burst is composed of $N_{pre}^{RA}$ acquisition preamble symbols, followed by $N_{pay}^{RA}$ pay-load symbols and $N_{guard}^{RA}$ guard symbols. The guard-time is necessary in practice to compensate for the incoming TDMA burst timing errors. This leads to the following equation:

$$N_{slot}^{RA} = N_{guard}^{RA} + N_{pre}^{RA} + N_{pay}^{RA} \tag{5.1}$$

In terms of symbols, the RA frame duration then corresponds to $N^{RA}_{frame} = N^{RA}_{slot}M^{RA}_{slots}$ and $T_F = N^{RA}_{frame}T_s$.

Considering a generic RA frame, the dependency on the frame index has been dropped for notation simplicity. The signals defining the RA channel behaviour have now been described. The discrete signal samples have been represented at symbol distance and it has been assumed for notation simplicity without loss of generality that relative STs burst delays occur in integer multiples of the symbol period itself. In such a setting, a generic discrete burst signal samples array $\overline{s}[i, n]$ generated by ST $\#i$ in slot $\#n$ is made up of a preamble sub-array $\overline{s}_{pre}[i]$, a payload sub-array $\overline{s}_{pay}[i, n]$ and an empty guard time sub-array $\overline{s}_{guard}$ so that:

$$\overline{s}[i, n] = \sqrt{P_{Tx}[i]}\,\overbrace{[\overline{s}_{pre}[i], \overline{s}_{pay}[i, n], \overline{s}_{guard}]}^{N^{RA}_{slot}} \tag{5.2}$$

$$\overline{s}_{pre}[i] = [c_1[i], c_2[i]...c_{N^{RA}_{pre}}[i]] \tag{5.3}$$

$$\overline{s}_{guard} = \overbrace{[0, 0, ...0]}^{N^{RA}_{guard}} \tag{5.4}$$

$$\begin{aligned}\overline{s}_{pay}[i, n] = \frac{1}{\sqrt{2}}[&d_{p,1}[i, n] + jd_{q,1}[i, n]...\\ &...d_{p,N^{RA}_{pay}}[i, n] + jd_{q,N^{RA}_{pay}}[i, n]]\end{aligned} \tag{5.5}$$

where $c_l[i]$ is the $l-$th symbol of the preamble binary ($\pm1$) BPSK modulated sequence and $d_{p,l}[i, n]$ and $d_{q,l}[i, n]$ are the $l-$th in-phase and quadrature binary ($\pm1$) payload symbols, respectively. The payload is dependent on slot $n$ due to the signalling information pointing to the twin burst relative to the current burst location. It has been assumed that the delay, amplitude and phase of the received signal at the gateway remains constant over a TDMA slot. Hence, the received signal samples can be written as:

$$\overline{r}[n] = \sum_{i=1}^{N_{ST}} \delta[i,n]L[i,n]\overline{s}[i,n]z^{-D[i,n]}.exp\{j(\phi[i,n] + \Delta w[i,n]t[n])\} + \overline{w}[n] \tag{5.6}$$

where $N_{ST}$ represents the total number of registered STs, $\delta[i,n]$ is 1 if the $i$-th terminal is active in slot $\#n$ and 0 otherwise, $L[i,n] < 1$ represents the signal attenuation, $0 \leq D[i,n] \leq N^{RA}_{guard}$ is the differential TDMA ST slot delay in symbols, $z^{-D[i,n]}$ is the delay operator shifting towards the right the array $\overline{s}[i,n]$ by $D[i,n]$ positions (symbols), $\phi[i,n]$ and $\Delta w[i,n]$ represent the carrier phase and frequency offset respectively, $t[n]$ is the time corresponding to the start of slot $n$ and $\overline{w}[n]$ is a complex array of $N^{RA}_{slot}$ elements each representing a circular symmetric white Gaussian noise with variance $\sigma^2_w$. The received preamble for user $\#i$ in slot $\#n$ has also been defined as the following sub-array derived from $\overline{r}[n]$:

$$\overline{r}_{pre}[n,i] = [r_{D[i,n]+1}, r_{D[i,n]+2}, ...r_{D[i,n]+N^{RA}_{pre}}] \tag{5.7}$$

In a similar way the received burst payload sub-array has been defined as:

$$\overline{r}_{pay}[n,i] = [r_{D[i,n]+N^{RA}_{pre}+1}, r_{D[i,n]+N^{RA}_{pre}+2}, ...r_{D[i,n]+N^{RA}_{pre}+N^{RA}_{pay}}] \tag{5.8}$$

### 5.3.2 Interference Cancellation Algorithm

In order to execute an iterative decoding process, the CRDSA burst demodulator accumulates in memory the baseband samples corresponding to an entire RA frame duration. The demodulator iteration counter is set to $N_{iter} = 1$ in the beginning. At every iteration, the following steps are carried out by the demodulator:

1. *Demodulation and decoding of clean bursts:* Clean bursts are those copies which were successfully transmitted without any collision. This means that for such bursts, the signal, noise and interference levels allow successful preamble recognition and payload decoding (e.g. packet 3 in slot 5 in Fig. 5.1).

(a) In this step the entire frame (each slot) is searched in parallel by the gateway burst demodulator for all the $S_{PR}$ possible burst preambles. Once the existence of one or more preamble sequences are detected in the slot by the multi-preamble searcher, the burst demodulator will estimate, as for a conventional one, the burst channel parameters (clock timing, carrier frequency and phase) and try to decode the payload information. If the preamble is detected and the burst payload Code Redundancy Check (CRC) authentication is successful, then the recovered burst is affirmed as "clean". After recovering the clean bursts, the conventional burst (D)SA demodulator will stop. It is assumed that $N_{recov}(N_{iter})$ bursts have been recovered at the current iteration.

(b) When a burst is correctly decoded it can be completely regenerated at complex baseband level by re-encoding and modulating the decoded relevant bits multiplexed with the current burst slot location signalling bits. In the twin burst regeneration the slot $n_r$ where the "replica" of the burst was transmitted (e.g. packet 3 in slot 4 in Fig. 5.1) is derived from the burst payload signaling information bits. Moreover, the acquisition preamble binary signature sequence and its timing are obtained from the burst demodulator preamble code correlator and timing estimation unit respectively.

(c) The same FEC of the useful payload bits also protects the twin burst signalling information and thus the signalling information is successfully recovered when the CRC check is positive. The stored information about the detected clean burst(s) twin(s) location within the frame is used in the next step along with their amplitude and clock information derived from the clean burst detection. Since the carrier phase is typically uncorrelated from burst-to-burst because of the local oscillator instabilities, the phase information extracted from the clean burst cannot be used for the twin burst.

2. *Contention Resolution Algorithms:* Following the previous step, the CRDSA demodulator then processes the slots where the replica burst of the "clean" bursts were transmitted and which have not been already identified in the earlier step (i.e. step 1-(a)) of the current iteration (e.g. packet 3 in slot 4 in Fig. 5.1). So the demodulator then acts on the slots where collision(s) took place (i.e. whereby more than one burst were simultaneously transmitted and destructively interacting). The CRDSA algorithm aspires at post-processing the stored frame samples to remove contention in some of the slots where collisions occurred.

It is assumed that in the current frame and iteration $N_{iter}$, the set of bursts identified by index $\overline{q} = [q_1, q_2, ...q_{N_{recov}(N_{iter})}]^2$ corresponding to STs $\overline{i} = [i_1, i_2, ...i_{N_{recov}(N_{iter})}]$ have been correctly decoded in slots $\overline{n} = [n_1, n_2, ...n_{N_{recov}(N_{iter})}]$. It is also assumed that the copies of the bursts $\overline{q}$ are located (according to clean packet signaling information) in slots $\overline{n}^r = [n_1^r, n_2^r, ...n_{N_{recov}(N_{iter})}^r]$ belonging to the same frame.

(a) It is assumed that the successfully detected clean bursts $\overline{q}$ from STs $\overline{i}$ in slots $\overline{n}$ provide an exact estimate of the signal amplitude $\hat{A}_{Rx}[i_k, n_k]$, $k = 1, 2, ...N_{recov}(N_{iter})$ and of the angular carrier frequency offset $\widehat{\Delta w}[i_k, n_k]$, $k = 1, 2, ...N_{recov}(N_{iter})$. The carrier phase between two successive bursts transmitted from the same ST is generally uncorrelated primarily due to the fast phase noise components of the ST. Received burst frequency, timing and amplitude arising from the same ST can rather be assumed almost constant within a frame thus $\widehat{\Delta w}[i_k, n_k^r] \simeq \widehat{\Delta w}[i_k, n_k]$, $\hat{A}[i_k, n_k^r] \simeq \hat{A}[i_k, n_k]$ and $\hat{\tau}[i_k, n_k^r] \simeq \hat{\tau}[i_k, n_k]$ for $k = 1, 2, ...N_{recov}(N_{iter})$. For notation simplicity in the following the carrier frequency offset has be dropped.

(b) The amplitude information of the replica burst slot $n_k^r$, $k = 1, 2, ...N_{recov}(N_{iter})$ can be accurately estimated from the twin "clean" burst which has been successfully detected in slot $n_k$ as: $\hat{A}[i_k, n_k^r] \simeq \hat{A}[i_k, n_k] \simeq \frac{1}{N_{pay}^{RA}} \mid \overline{r}_{pay}[i_k, n_k].\{\hat{s}_{pay}^*[i_k, n_k]\}^T \mid$, where the complex array $\hat{s}_{pay}[i_k, n_k]$ represents the estimated payload transmitted symbols as obtained by re-encoding at the CRDSA demodulator the decoded bits, the operator $^T$ indicated array transposition and $^*$ the complex conjugate. Having assumed a correct decoding of the payload encoded bits it follows that $\hat{s}_{pay}[i_k, n_k] = s_{pay}[i_k, n_k]$.

(c) For each replica burst slot $n_k^r$, $k = 1, 2, ...N_{recov}(N_{iter})$, the carrier phase information corresponding to this slot for user $i_k$ can be derived by correlating the stored slot $n_k^r$ soft samples $\overline{r}_{pre}[i_k, n_k^r]$ with the user $i_k$ preamble sequence $\overline{s}_{pre}[i_k]$ of length $N_{pre}^{RA}$ symbols as: $\hat{\phi}[i_k, n_k^r] \simeq \arg\{\overline{r}_{pre}[i_k, n_k^r].\{\overline{s}_{pre}^*[i_k]\}^T\}$ where it was assumed that the burst timing offset error is negligible. This timing estimate can be based on the successfully detected packet from user $i_k$ detected in slot $n_k$.

(d) Colliding burst from users $i_k$ in slot $n_k^r$ can now be removed by IC (e.g. in Fig. 5.1 packet 3 can be removed from slot 4):

$$\begin{aligned}\overline{r}[n_k^r, N_{iter}+1] &\simeq \overline{r}[n_k^r, N_{iter}] - \hat{A}[i_k, n_k] \\ &.exp[j(\hat{\phi}[i_k, n_k^r] + \widehat{\Delta w}[i_k, n_k]t[n_k^r])] \\ &.[\overline{\hat{s}}_{pre}[i_k], \overline{\hat{s}}_{pay}[i_k, n_k]]\end{aligned} \tag{5.9}$$

(e) The iteration counter in incremented as: $N_{iter} = N_{iter} + 1$.

(f) Having introduced the CRDSA demodulator maximum number of iterations $N_{iter}^{max}$, if $N_{iter} = N_{iter}^{max}$ then stop, else go to step 1-(a).

## 5.4 Simulation results and conclusions

### 5.4.1 Existing simulation results

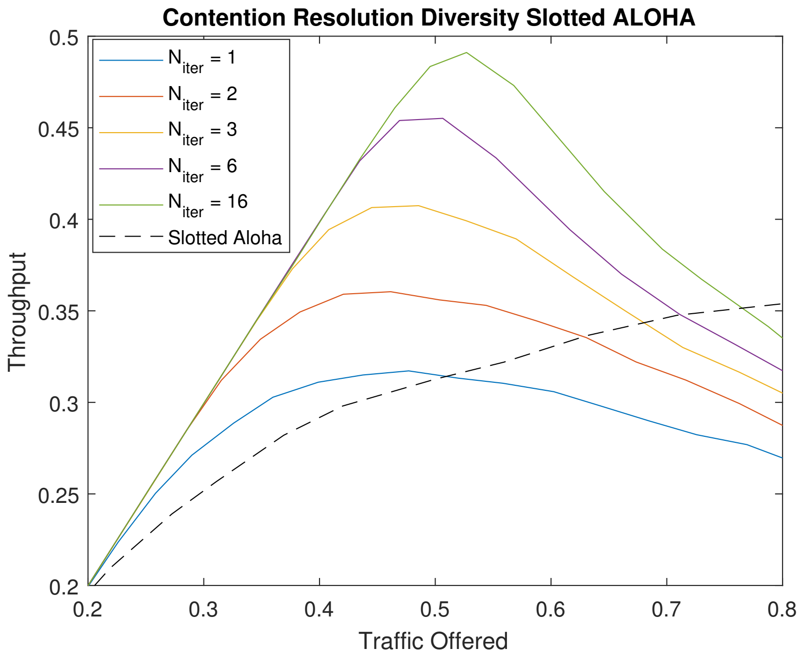


Figure 5.2: Simulated results for the CRDSA throughput (ideal channel estimation for IC) versus the normalized channel loading for $N_{iter} = 1, 2, 3, 6, 16$. Slotted Aloha (SA) performance is also reported for comparison.

The performance parameter used in Fig. (5.2) is throughput (measured in useful packets received per slot) vs. load (measured in useful packets transmitted per slot). One slot can carry one data packet. In Fig. 5.2, the throughput of the CRDSA protocol has been simulated versus the normalized MAC load for a variable number of maximum iterations in the contention resolution process ($N_{iter}^{max} = 1, 2, 3, 6, 16$) and under the assumption of perfect channel estimation for IC. With the increase in number of maximum iterations and better interference cancellation, the throughput performance becomes better. However, it is interesting to observe that there is a diminishing return advantage in increasing the number of maximum CRDSA demodulator iterations $N_{iter}^{max}$.

### 5.4.2 New simulation results

In Fig. (5.2), each curve corresponding to a particular value of $N_{iter}^{max}$ uses a probabilistic random number of replications for packet transmission. We now use the deterministic scheme with $k$ being the number of replications (diversity order). We try to observe the impact of diversity order $k$ on the throughput performance for a given value of $N_{iter}^{max}$. We have simulated the throughput performance for different values of $k$ at $N_{iter}^{max} = 6$.

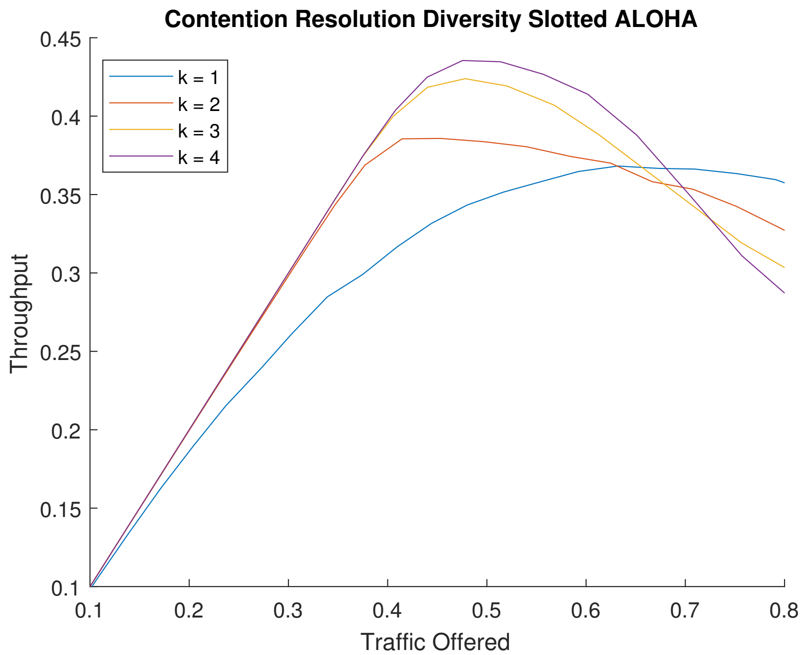


Figure 5.3: Simulated results for the CRDSA throughput (ideal channel estimation for IC) versus the normalized channel loading for $N_{iter} = 6$, different k

Fig. (5.3) shows the throughput versus traffic offered plot for $N_{iter}^{max} = 6$ and different values of $k = 1, 2, 3, 4$. As evident from the plot, a higher diversity order $k$ leads to a better throughput for a given value of offered traffic. In Fig. (4.5) in the previous chapter, we plotted the throughput performance for different values of $k$ in Diversity Slotted ALOHA (DSA) and observed that the throughput performance is almost the same under light traffic while for heavy traffic, a higher diversity scheme gave a poorer throughput performance. On the contrary, in CRDSA as evident from Fig. (5.3), a higher diversity scheme gives a better performance till a considerable amount of normalized traffic (till $G = 0.7$). This is because of the Successive Interference Cancellation (SIC) which takes place in CRDSA. More number of replications lead to a better performance because SIC helps in correct packet reception. However, when traffic is considerably increased ($G > 0.7$), the number of collisions become very large and SIC does not help much.

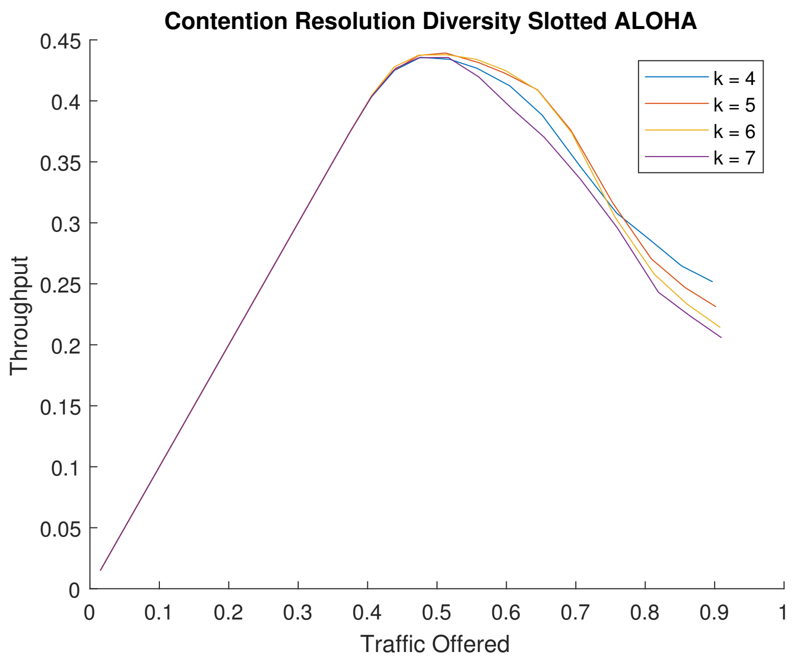


Figure 5.4: Simulated results for the CRDSA throughput (ideal channel estimation for IC) versus the normalized channel loading for $N_{iter} = 6$, different k

In Fig. (5.3) we saw that at $G < 0.7$, a higher $k$ gives better throughput performance. However, it is logical to assume that the performance would not continuously increase with an increase in $k$. The performance initially increases as $k$ rises because of the benefits of SIC. However, SIC can help only up to a limit. If the number of copies become too high, SIC would not help and the performance should reduce. To verify this, we plotted the throughput vs traffic offered at $N_{iter}^{max} = 6$ for much higher values of $k$ in Fig. (5.4) and (5.5). Fig.(5.4) shows the performance for $k = 4, 5, 6, 7$ and Fig. (5.5) for $k = 4, 8, 12, 16$. As expected, the throughput performance almost saturates as $k$ increases from $4$ to $7$, and reduces considerably as $k$ is further increased.

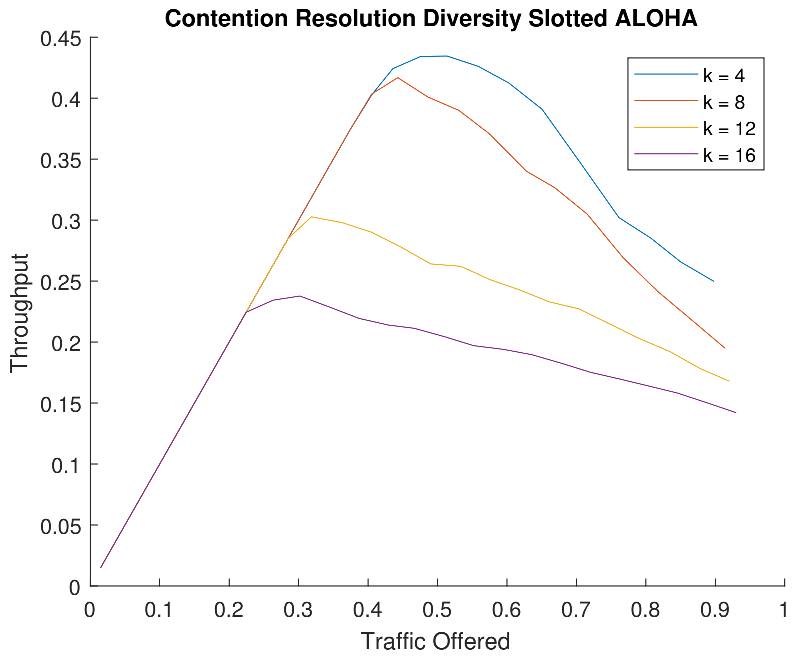


Figure 5.5: Simulated results for the CRDSA throughput (ideal channel estimation for IC) versus the normalized channel loading for $N_{iter} = 6$, different k

We now look at the Packet Loss Ratio (PLR) performance of CRDSA with varying diversity order $k$. In section (4.3.3), we looked at the PLR performance in case of DSA and found out that the diversity schemes ($k > 1$) perform better than classic SA ($k = 1$) only for very light traffic ($G < 0.18$). Fig. (5.6) shows the plot of PLR versus input traffic for different values of $k$ in case of CRDSA.

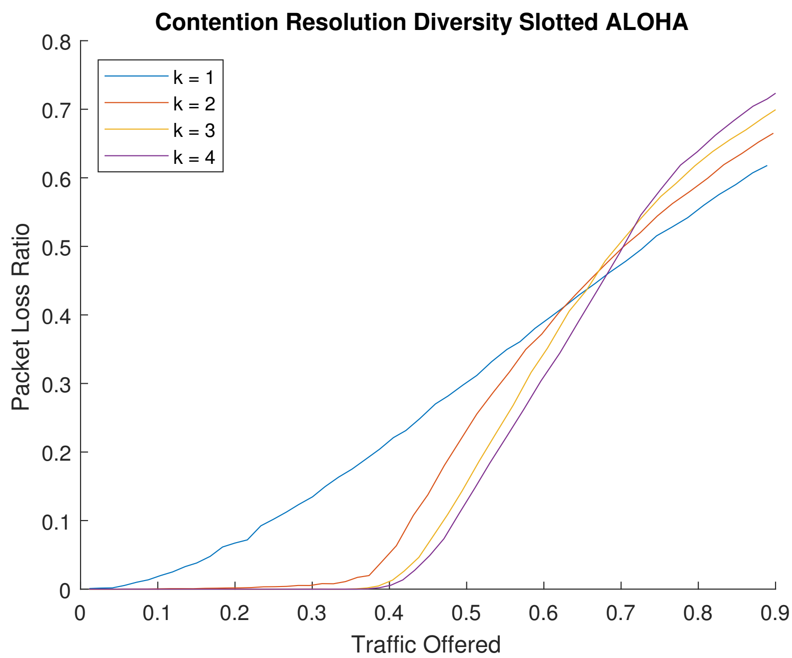


Figure 5.6: Plot of the CRDSA Packet Loss Ratio versus normalized traffic offered for $N_{iter} = 6$, various k

As evident from the plot, the diversity schemes ($k > 1$) perform better than the SA ($k = 1$) scheme till much higher value of input traffic ($G < 0.65$) compared to DSA ($G < 0.18$). Moreover, among the various diversity schemes, a higher value of the diversity order performs better (for $G < 0.65$). In CRDSA, the diversity schemes perform better till a much higher input traffic than in DSA because of the Successive Interference Cancellation (SIC) which leads to successful decoding of more packets. A higher value of the diversity order performs better because the effect of SIC is more in case of more number of replications. As expected, if the traffic is too high ($G > 0.65$), the number of collisions become so huge that SIC becomes ineffective and a higher number of replications lead to poorer performance (higher PLR). Under such high input traffic ($G > 0.65$), the classic slotted ALOHA ($k = 1$) performs the best.

# CHAPTER 6

# Conclusions and Future Work

The main purpose of this work was to successfully illustrate the existing performance evaluation (in terms of throughput, delay and Packet Loss Ratio) of the improved slotted ALOHA (DSA and CRDSA) schemes and to demonstrate the impact of parameters like diversity order and number of successive interference cancellation iterations on these performance measures. We saw that the performance of these schemes are largely influenced by such parameters and it is important to know how they affect the realization of the DSA and CRDSA schemes. The optimal values of the parameters result in the obtainment of most gains from the enhanced SA schemes. We also looked at the comparison of the deterministic and probabilistic version of the schemes. However, we assumed that the transmitter has information about the number of users in the system for all the simulations.

At present, there has been a shift in the wireless landscape to incorporate more networks with large numbers of unattended devices which seek to distribute their information sparingly. Hence, a transformation of the existing multiple access schemes is required to accommodate systems which confirm to this paradigm shift. With the massive increase in the number of wireless machines, the future access points may have to back sporadic transmissions from a huge number of unattended machines. The design of massive uncoordinated multiple access schemes for such systems based on the improvements to slotted ALOHA has gained a lot of interest in particular. The implementation of the random access strategy in the existing results to augment the performance of slotted ALOHA systems assume that the number of users is known at the transmitters. The future works can aim to design innovative formulations of the uncoordinated slotted multiple access problem in which the number of users in the system is not known, but which include multiple access points with overlapping users.

# REFERENCES


1. **A. Taghavi, J.-F. C., A. Vem** and **K. R. Narayanan** (2016). On the design of universal schemes for massive uncoordinated multiple access. *in IEEE International Symposium on Information Theory (ISIT)*, 345–349.

2. **Abramson, N.** (Jan. 1977). The throughput of packet broadcasting channels. *IEEE Trans. Commun.*, **vol. COM-25**(no. 1), 117–128.

3. **Abramson, N.** (Nov. 1970). The aloha system - another alternative for computer communications. *in Proc. AFIPS Conf.*, **vol. 37**, 281–285.

4. **Choudhury, G. L.** and **S. S. Rappaport** (Mar. 1983). Diversity aloha - a random access scheme for satellite communications. *IEEE Trans. Commun.*, **vol. 31**(no. 3), 450–457.

5. **del Rio Herrero, O.** and **R. D. Gaudenzi** (June 2009). A high-performance mac protocol for consumer broadband satellite systems. *in Proc. 27th AIAA International Commun. Satellite Syst. Conf. (ICSSC), Edinburgh, UK*.

6. **DeRosa, J. K.** and **L. H. Ozarow** (Jan. 1978). Packet switching in a processing satellite. *Proc. IEEE*, **vol. 66**, 100–102.

7. **E. Casini, R. D. G.** and **O. del Rio Herrero** (Apr. 2007). Contention resolution diversity slotted aloha (crdsa): an enhanced random access scheme for satellite access packet networks. *IEEE Trans. Wireless Commun.*, **vol. 6**(no. 4), 1408–1419.

8. **E. Paolini, G. L., C. Stefanovic** and **P. Popovski** (2015). Coded random access: applying codes on graphs to design random access protocols. *IEEE Commun. Mag.*, **vol. 53**(no. 6), 144–150.

9. **Ferguson, M. J.** (Nov. 1975). On the control, stability and waiting time in a slotted aloha random-access system. *IEEE Trans. Commun.*, **vol. COM-23**, 1306–1311.

10. **H. Kobayashi, Y. O.** and **D. Huynh** (Jan. 1977). An approximate method for design and analysis of an aloha system. *IEEE Trans. Commun.*, **vol. COM-25**, 148–158.

11. **J. K. DeRosa, L. H. O.** and **L. W. Weiner** (Oct. 1979). Efficient packet satellite communications. *IEEE Trans. Commun.*, **vol. COM-27**, 1416–1422.

12. **Kleinrock, L.** and **S. Lam** (Apr. 1975). Packet switching in a multiaccess broadcast channel: performance evaluation. *IEEE Trans. Commun.*, **vol. 23**(no. 4), 410–423.

13. **Liva, G.** (2011). Graph-based analysis and optimization of contention resolution diversity slotted aloha. *IEEE Trans. Commun.*, **vol. 59**(no. 2), 477–487.

14. **Liva, G.** (Jan. 2010). A slotted aloha scheme based on bipartite graph optimization. *in Proc. International ITG Conf. Source Channel Coding, Siegen, Germany*.

15. **M. Luby, A. S., M. Mitzenmacher** and **D. A. Spielman** (Feb. 2001). Improved low-density parity-check codes using irregular graphs. *IEEE Trans. Inf. Theory*, **vol. 47**(no. 2), 585–598.

16. **Metcalfe, R.** (Jan. 1973). Steady-state analysis of a slotted and controlled aloha system with blocking. *in Proc. 6th Hawaii Int. Conf. Syst. Sci.*.

17. **Narayanan, K. R.** and **H. D. Pfister** (2012). Iterative collision resolution for slotted aloha: An optimal uncoordinated transmission policy. *in Intern. Symp. Turbo Codes Iter. Inf. Proc. (ISTC), IEEE*, 136–139.

18. **Patel, P.** and **J. Holtzman** (June 1994). Analysis of a simple successive interference cancellation scheme in a ds/cdma system. *IEEE J. Select. Areas Commun.*, **vol. 12**(no. 5), 796–807.

19. **Raychaudhuri, D.** (Feb. 1984). Aloha with multipacket messages and arq-type retransmission protocols-throughput analysis. *IEEE Trans. Commun.*, **vol. 32**(no. 2), 148–154.

20. **Roberts, L. G.** (Apr. 1975). Aloha packet system with and without slots and capture. *Comp. Commun. Review*, **vol. 5**, 28–42.

21. **T. J. Richardson, A. S.** and **R. L. Urbanke** (Feb. 2001). Design of capacity-approaching irregular low-density parity-check codes. *IEEE Trans. Inf. Theory*, **vol. 47**(no. 2), 619–637.