Slotted ALOHA Random Access: Considering Priority, and Energy Efficiency

by

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Abstract

ALOHA is a random medium access control (MAC) protocol, designed over 50 years ago. Due to its widespread applications in wireless Machine-to-Machine (M2M) communications, and also deployment of recently developed ideas borrowed from coding theory, ALOHA has recently attracted lots of attention. As a result, different versions of ALOHA that have significantly improved the scheme throughput compared to the original ALOHA have been recently created. This thesis focuses on two of the recent versions of ALOHA protocol.

In the first part of our contributions in this thesis, we study the achievable throughput region for a network consisting of more than 1 class of users with different priority, and desire for throughput achievement. Considering framed slotted ALOHA with irregular repetition and successive interference cancellation (SIC), we find the best possible throughput region, and we also show how to achieve this region. We achieve this throughput region by selectively turning users of different groups on and off, based on their desired sets of throughputs.

In the second part of this thesis, we investigate several modifications on a recently proposed ALOHA random access protocol, namely frameless slotted ALOHA random access. Frameless slotted ALOHA random access protocol has been able to achieve the highest throughput among all the slotted ALOHA schemes. In frameless slotted ALOHA each user independently accesses the wireless medium and all users have the same probability of access. In this work, we propose two adaptive access techniques that will help reduce the energy consumption of wireless communication networks of relatively small size [25-200] without loss of throughput. The amount of reduction in the energy consumption depends on the number of users in the network.

To My Beloved Family

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List of Abbreviations

List of commonly used abbreviations

WSN	Wireless Sensor Network
Machine-to-Machine	M2M
CSMA	Carrier Sense Multiple Access
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
MAC	Medium Access Control
BS	Base Station
SIC	Successive Interference Cancellation
BP	Belief Propagation
RFID	Radio Frequency Identification
QoS	Quality of Service
WBAN	Wireless Body Area Network

Chapter 1

Introduction

Many communication networks consist of a number of users intended to use a shared medium. There are two types of medium access approach for the users of such a network. In one approach, users share the medium in an organized predetermined way avoiding any kind of interference. In the other approach, however, users share the medium in a random, and distributed manner. In networks with random behavior, like wireless sensor networks (WSNs), machine-to-machine (M2M) communications, mobile ad hoc networks, and so many other wireless networks, random access is the primary method of medium access[1–3]. ALOHA[4], carrier sense multiple access (CSMA), and its versions with collision detection, and collision avoidance, i.e. CSMA/CD, and CSMA/CA [5, 6] are among different random medium access control (MAC) protocols.

ALOHA as a random MAC protocol has been designed in 1970 [4] to support wireless data connectivity between Hawaiian Islands. ALOHA and its various slotted versions have long been used as random distributed medium access protocols for radio channels. They have been used in satellite networks and cellular telephone networks for the sporadic transfer of data packets[7].

Recent widespread applications of wireless M2M communications together with new ideas borrowed from modern coding theory that can significantly improve the throughput of ALOHA has resulted in new interest in ALOHA and its modifications.

In the following, all different versions of ALOHA random access since its inception until recently are discussed. The main focus of this thesis is on the recent improvements in ALOHA random access protocol.

1.1 ALOHA, Since Inception Until Now

The first version of ALOHA, designed in 1970, is also known as pure ALOHA. This is a distributed random access in which each user transmits whenever it has a packet for transmission. If the receiver receives the packet with no interference, it sends an acknowledgment to the sender of that packet, otherwise the transmitter does not receive an acknowledgment and has to resend its packet after a random delay. There is no time slot considered in pure ALOHA, and all the packets are of the same size. Since there is no central organization, transmissions of different users may collide (overlap in time). Also, there can be time periods over which nobody transmits. The achievable throughput, defined as the average number of successful packet transmissions per packet time, in this scheme is $\frac{1}{2e}$ packets per time slot, where e is the Neper number approximately, 2.718 .

Attempting to reduce the number of collisions in pure ALOHA protocol, slotted ALOHA random access was proposed in [8]. In slotted ALOHA the shared access time is divided into slots of equal duration[1], in which synchronized users contend to transmit their data packets with equal probability. In this protocol, users are only allowed to send their packets at the beginning of a time slot. Therefore, if a user decides to have a transmission in the middle of a time slot, it should wait until the beginning of the next time slot.

There are three cases that may happen in an arbitrary slot in slotted

[1]The duration of a slot is equal to the time needed for a packet to be transmitted.

ALOHA protocol: a) no transmission (idle slot), b) only one transmission (singleton slot), c) more than one transmission (collision slot). The same as pure ALOHA, in slotted ALOHA if the receiver or base station (BS) receives a collision free packet in a singleton slot, the corresponding user receives an acknowledgment. Otherwise, the corresponding participant users in that collision will have retransmissions in some later time slots with a random delay. This random access scheme doubles the achievable throughput of pure ALOHA reaching a throughput of $\frac{1}{e}$.

Framed slotted ALOHA [9] is a version of slotted ALOHA where the shared access time is divided into frames, consisting of M time slots. Each user may have a transmission in a frame with probability p, as the users probability of access to the shared medium. Every user intended to have a transmission in a frame, randomly and uniformly selects one of the time slots in the frame to transmit its packet in that time slot. The same as the slotted ALOHA scheme, only collision free slots, i.e. singleton slots are considered as successful transmissions in a frame.

In an attempt to improve throughput in framed slotted ALOHA, the authors in [10] proposed the idea of transmission of several replicas of the same user message in a frame. This idea was further developed in [11] in 2007, by introducing successive interference cancellation (SIC) technique which considerably increased the throughput of framed slotted ALOHA. This paper proposes regular repetition of users messages, meaning that all the users intended to have transmissions transmit the same number of replicas of their messages in a frame. Replication happens in a way that in the beginning of a frame, each user that is about to transmit its message, chooses a specific number of time slots randomly and uniformly from that frame and transmits its message in those slots. Each replica of a user message has a pointer to other replicas of that user. In framed slotted ALOHA with repetition, received packets by the BS from different users in one time slot are summed up. Thus, if the BS has resolved one message from a singleton time slot, by canceling that message from the summations, it maybe able to resolve some other messages. In the next chapter SIC resolution algorithm is discussed with details.

In 2011, the author of [12] has improved the idea of repeating messages using an irregular repetition method. This means that the users repetition of their messages should be based on a probability distribution function. For example, users intended to transmit their messages in a frame, will have two replicas with probability 0.5, three replicas with 0.25, and four replicas with 0.25 probability, rather than all transmitting the same number of replicas. By doing optimization over this probability distribution function, Liva has been able to considerably improve throughput of framed slotted ALOHA with SIC. Next chapter presents details regarding this optimization framework.

Analogies between SIC in framed slotted ALOHA and iterative belief-propagation (BP) decoding[13] of erasure-correcting codes was discovered in [12] as a breakthrough in the area of coded random access. Using the theory and tools of codes-on-graphs formed the foundation for coded slotted ALOHA. Using SIC in framed slotted ALOHA random access, the authors of [14–17] have attempted to find optimum distributions and coding patterns over the users data transmissions that lead to ultimate throughput of 1 packet per time slot when the number of users N tends to infinity. Inspired by the concept of rateless coding [18], frameless slotted ALOHA approach is introduced in [19], and elaborated in [20], in 2013.

Our contribution in this thesis consists of two parts. The first part is based on framed slotted ALOHA with irregular repetition, and SIC, while the second part is based on frameless slotted ALOHA.

1.2 Motivations

In this thesis, we are going to attack two different problems based on the most recent attempts on the throughput improvement of framed slotted ALOHA with SIC, and frameless slotted ALOHA. This section motivates our contributions, and gives a summary of our contributions.

1.2.1 Slotted ALOHA and Priority

In the era of the Internet of things, random access will have many civil and industrial applications. Moreover, in many cases, when different users share the same medium, priority classes are defined. For example, in a sensor network, some information may have priority over the others.

In the first part of this thesis, we consider the framed slotted ALOHA with irregular repetition and SIC scheme, when users belong to different priority classes. In this part, we find the best possible throughput region for different classes of a network which are using the same channel. We also discuss how to achieve any point of this region, by forcing special methods of transmission over different classes.

1.2.2 Slotted ALOHA and Energy Efficiency

Slotted ALOHA has found its plethora of applications in different wireless communication setups. These include new emerging technologies such as radio frequency identification (RFID) networks, WSNs and M2M communication networks. In most of these applications users use small size attached batteries as their only source of energy and they seriously need to be designed with energy optimization in mind.

Thus, our focus in the second part of this thesis is on the improvement of energy efficiency in frameless slotted ALOHA scheme, as the slotted ALOHA scheme with the highest throughput.

1.3 Summary of Contributions

1.3.1 Slotted ALOHA and Priority

Considering a network with N users of k different classes, transmitting their messages in a frame with N time slots, we achieve the best throughput region, and we also show how to achieve this region. We have obtained this throughput region, by selectively making users of the different k classes on and off in a way that the total distribution of the N users remains the same as the optimized distribution for irregular repetition of a network with a group of N users.

We have also presented the best achievable throughput region for the case when framed slotted ALOHA without SIC is the random access protocol. We have come up with this throughput region by performing optimizations over the probability of access of different classes of users.

1.3.2 Slotted ALOHA and Energy Efficiency

In order to further increase the energy efficiency of frameless ALOHA protocol without compromising its throughput, we suggest a modified frameless ALOHA schemes. In our modified frameless slotted ALOHA, the access probability at the users adaptively changes. More specifically, all users start with the same access probability at the first time slot of each frame. However, each user updates its current access probability based on whether it has transmitted in the previous time slot or not. That is, if the user transmitted in the previous time slot, it decreases its current access probability. On the other hand, if the user did not make a transmission in the previous time slot, the access probability increases. To achieve the best energy efficiency performance, we jointly optimize the stopping criterion of the frameless ALOHA as well as the step size that the users apply for increasing or decreasing the transmission probability.

1.4 Organization of This Thesis

Chapters 2 gives the necessary background on all different ALOHA schemes from the beginning until recently, which will be required to follow this thesis. Chapter 3 focuses on our first problem. In this chapter, we introduce three different methods of transmission in framed slotted ALOHA for a network of k different classes to achieve the best throughput region. We present the best possible throughput region that can be reached for these network setups, and eventually, we compare the three proposed methods. Chapter 4 focuses on our second problem. In this chapter, we define our proposed techniques and analysis to improve the energy efficiency of frameless slotted ALOHA scheme. We also present our simulation results and compare the original frameless slotted ALOHA scheme with our adaptive transmission techniques in terms of energy efficiency. Finally, Chapter 5 concludes the thesis.

Chapter 2

Background

In this chapter, we review the necessary background to follow this thesis. We present throughput derivations for different ALOHA schemes, and we go over details regarding some previous works that we are going to further develop in this thesis. Furthermore, we review some of the existing work related to our contributions.

2.1 Analysis and Explanation of Different Versions of ALOHA

2.1.1 Pure ALOHA

In order to calculate the throughput of this scheme, we assume that the users in the network produce their data packets totally random in time. Hence the number of packets in a given time period follows a Poisson distribution. We denote the time that an arbitrary user starts its transmission by t, and the time duration needed for a packet to be transmitted by L. Thus, if any other user transmits between $t - L$ and $t + L$ a collision is caused. We consider L as the unit of time, and G as the average traffic load per unit of time. In other words, G is the rate of Poisson distribution. Throughput, T, as the probability to receive a successful transmission per unit of time, would be calculated as:

$$T = Ge^{-2G}. \tag{2.1}$$

This is the product of traffic load per time unit G, and the probability of not having any other transmission in a specific time unit. The maximum of this equation happens when $G = 0.5$, which gives a small throughput as $\frac{1}{2e}$, or approximately 0.18.

2.1.2 Slotted ALOHA

The same as pure ALOHA, in slotted ALOHA users packet generation is considered to have a Poisson distribution with rate G, as the traffic load. So throughput of this scheme would be:

$$T = Ge^{-G}, \tag{2.2}$$

which gives a maximum throughput, equal to $\frac{1}{e} \simeq 0.37$, when $G = 1$. Here, the maximum throughput is double the amount obtained for pure ALOHA. This is due to the fact that, in slotted ALOHA possible collisions are half of the number of collisions that happen in pure ALOHA.

2.1.3 Framed Slotted ALOHA

Throughput of a network consisting of N users transmitting their data packets with access probability p, in a frame consisting of M time slots, can be obtained from the following equation:

$$T = \frac{Np(1-\frac{p}{M})^{N-1}}{M}. \tag{2.3}$$

The maximum of this equation happens at $p = \dfrac{M}{N}$ for $M \leq N$, and at $p = 1$ for $M > N$. Which gives, maximum throughput, T_{max}, as:

$$T_{max} = \begin{cases} (1 - \dfrac{1}{N})^{N-1} & M \leq N \\ \dfrac{N(1 - \frac{1}{M})^{N-1}}{M}. & M > N \end{cases} \tag{2.4}$$

As in most cases $M \leq N$, we can use the first equation in (2.4) for T_{max}. This is approximately equal to $\frac{1}{e}$ for large N, meaning that in networks with a large number of users, the framed slotted ALOHA protocol has approximately the same performance as the slotted ALOHA scheme. The difference between slotted ALOHA and framed slotted ALOHA is that in framed slotted ALOHA, there is a synchronization among the users on the basis of a frame rather than a time slot. At the start of a frame, users should decide where to have their transmissions in a frame, and at the end of a frame, the BS sends feedback to the users to inform them weather their transmissions have been successful, or not. So, this way the number of feedbacks are reduced with respect to the number of feedbacks when slotted ALOHA is the random access protocol.

2.1.4 Successive Interference Cancellation (SIC)

As discussed in the previous chapter, framed slotted ALOHA was further improved by having users transmit more than one replica of their packets of data, or messages. Using message repetition together with SIC at the BS considerably improved the throughput. In this part we explain SIC with details.

SIC was initially applied to framed slotted ALOHA in [11]. SIC is able to significantly improve the throughput performance by resolving some of the collisions. The receiver first resolves the singletons received in a frame. Then, by the aid of pointers contained in those singletons, their corresponding interferences in other slots are canceled. By doing such, some other singletons may be discovered. So this process is iteratively repeated until either there is no more singletons or all the users messages in that frame are resolved.

A toy example of execution of SIC is shown in Figure 2.1. In this example, there are 4 time slots in the frame. In the graphical representation users are on the left side of the graph and time slots are on the right side of the graph. Each user is connected to the slots that has a transmission in them. First singleton happens in the second time slot, s_2, which leads to resolving transmitted packet by u_1. Now, the pointer in the received packet in s_2 helps to cancel the interference of u_1 packet from s_4, and this means that s_4 is now a singleton. This consequently helps the resolution of u_2 packet. Eventually, by canceling the interference of u_2 packet, u_3 packet can be resolved. In this simple example, SIC algorithm increased throughput from $\frac{1}{4}$ to $\frac{3}{4}$.

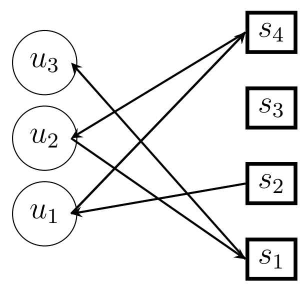

Figure 2.1: Graph representation of SIC procedure.

There are other performance metrics rather than throughput, for example delay which is critical in some networks. SIC improves throughput performance of networks, however, may worsen its delay performance.

2.1.5 Framed Slotted ALOHA with Irregular Repetition, and SIC

This protocol [12] is our primary framework to study the first problem in this thesis, so we go over this random access protocol in details.

There are N users in a network, and there are N time slots in a frame. Consider that out of this number of users only m users are allowed to transmit their messages in a frame. So the traffic load, G, is defined as $G = \frac{m}{N}$, which is the number of messages to be transmitted per time slot[1]. The m number of users who are about to transmit their messages, will have l, $l \in \{1, 2, \dots, N\}$ replicas of their messages in a frame, with probability Λ_l where $\sum_{l=1}^{N} \Lambda_l = 1$. So, the polynomial representation of the probability distribution function over the number of repetition of users messages is defined as, $\Lambda(x) \triangleq \sum_{l=1}^{N} \Lambda_l x^l$. [12] defines user degree and slot degree as the number of lines connected to a slot node, and user node in the graphical representation, respectively. So we can also name $\Lambda(x)$ as the user degree distribution in this setting. Polynomial representation of slot degree distribution can be denoted as $\Psi(x)$, $\Psi(x) \triangleq \sum_{l=1}^{m} \Psi_l x^l$, where Ψ_l denotes the probability that a slot has l connections. So, it is obvious that user degree distribution is under the control of a system designer, while slot degree distribution is not. Actually, $\Psi(x)$ can be derived from $\Lambda(x)$.

In the graphical representation, users and slots are considered as nodes, and lines are considered as edges. Degree distributions can also be defined from an edge perspective. If we define λ_l as the probability that an edge is connected to a degree-l user node, and ρ_l as the probability that an edge is connected to a degree-l slot node, λ_l, and ρ_l can be obtained from below equations:

$$\lambda_l = \frac{l\Lambda_l}{\sum_{l=1}^{N} l\Lambda_l}, \tag{2.5}$$

$$\rho_l = \frac{l\Psi_l}{\sum_{l=1}^{m} l\Psi_l}. \tag{2.6}$$

We can have their corresponding polynomial degree distributions as the follow-

[1]As it is important to resolve each of the users messages, we do not count the repeated messages, and we only count for the actual load.

ing:

$$\lambda(x) \triangleq \sum_{l=1}^{N} \lambda_l x^{l-1} = \frac{\Lambda'(x)}{\Lambda'(1)}, \tag{2.7}$$

$$\rho(x) \triangleq \sum_{l=1}^{m} \rho_l x^{l-1} = \frac{\Psi'(x)}{\Psi'(1)}. \tag{2.8}$$

Through tree analysis in [21], Liva has provided a recursive formula for the probability of not being able to resolve an edge either connected to a user, or a slot node in the graphical representation. He finds this recursive formula for framed slotted ALOHA with SIC, user degree distribution $\Lambda(x)$, and traffic load G.

Let us denote the probability that an arbitrary edge connected to a user node is unknown by q_i. In a similar way, considering a slot node, p_i denotes the probability that an arbitrary edge connected to this node is unknown. The evolution of the average erasure probabilities, during the i^{th} iteration, i.e., the recursive formula for the probability of failure to resolve an edge is presented below:

$$q_i = \lambda(p_{i-1}), \tag{2.9}$$

$$p_i = 1 - \rho(1 - q_i). \tag{2.10}$$

If we replace (2.10) in (2.9), it gives $q_i = \lambda(1 - \rho(1 - q_{i-1}))$. Now if we iterate this equation starting with $q_0 = 1$ (as there are no revealed edges at the beginning of the process.), after I iterations, we reach to an approximate value for the probability of an arbitrary edge being unknown.

If we denote the probability of failure to recover an arbitrary edge connected to an arbitrary user node, after I iterations by p_I, throughput after this I

iterations would be $T_I = G(1 - \Lambda(p_I))$.

It is obvious from above recursive equations, that if we force the failure probabilities of edge recovery, q, and p to decrease iteration by iteration, we will be able to increase the achieved throughput after a certain number of iterations. Liva has set a condition on q to decrease it in each iteration, and thus make the throughput $T = G(1 - \Lambda(p))$ as high as possible (we removed the index I as we assume that a large enough number of iterations of SIC are performed to resolve user messages). This condition leads to the inequality $q > \lambda(1 - \rho(1 - q))$. This inequality ensures that after each iteration, the failure probability decreases. Liva has provided an approximation for $\rho(x)$ when $m \to \infty$ as $e^{-G\Lambda'(1)(1-x)}$. So, the inequality converts to:

$$q > \lambda(1 - e^{-qG\Lambda'(1)}), \quad \forall q \in (0, 1]. \tag{2.11}$$

This yields a threshold for G, as G^* up to which the probability of message recovery failure, i.e, $\Lambda(p)$ is negligible and thus T is equal to G. Optimization gaol in Liva's paper is to find a distribution over the number of repetitions, i.e. $\Lambda(x)$ that makes G^* and thus T as high as possible. It is worth mentioning that derivation of the recursive formulas comes from an asymptotic analysis for large networks; however, simulation results for short frames confirms the validity of this optimization criterion. Simulation result show that by setting the maximum number of repetitions to 8, distribution $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$, will give $G^* = 0.938$, asymptotically. If we set the maximum repetition rate to higher values, the achieved G^* would get closer to 1. However, to make it easier to implement we will use the distribution, $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$ to develop our studies in the first part of this thesis. In Chapter 3, we will find the best throughput region for a network with non-homogeneous groups of users, based on this distribution.

In the following, we present concepts regarding frameless slotted ALOHA protocol, as the second part of this thesis focuses on frameless slotted ALOHA.

2.1.6 Frameless Slotted ALOHA

In a recent study [19], a new technique, called frameless ALOHA, has been developed aiming at improving the network throughput. Unlike conventional framed slotted ALOHA protocols and inspired by the concept of rateless coding [18], frameless ALOHA does not assign a fixed number of slots to each frame. Instead, the authors define a stopping criterion based on the number of resolved packets, and the instantaneous throughput at the destination. That said, a frame ends when such a criterion is met regardless of the number of slots in the frame. Using such a dynamic frame length and employing SIC at the destination, frameless ALOHA increases the network throughput, and consequently its energy efficiency significantly comparing to the previous versions of ALOHA protocol. As discussed earlier, using SIC is motivated by BP decoding of rateless codes. However, there are some differences between the underlying ideas used in frameless slotted ALOHA and rateless coding. In the following, we briefly elaborate these differences.

In rateless coding, transmitter sends encoded symbols continuously until it receives a feedback from the BS indicating the successful resolution of the intended message. While in rateless coding the receiver is aimed at decoding the whole message that the transmitter is intended to transmit, it is impractical for the frameless slotted ALOHA scheme to have such a stopping criterion which translates to resolving the whole users messages. In frameless slotted ALOHA, users transmit their messages continuously, until they receive a feedback from the BS to stop. The set of time slots in which users are having their transmissions is called a contention period. The BS decides to end a contention period when a stopping condition is met. The major difference between frameless slotted ALOHA and rateless coding is the distributed coding in frameless slotted ALOHA rather than centralized coding in rateless coding.

In the following, we present the system model for a network with frameless slotted ALOHA.

2.1.6.1 System Model

Frameless slotted ALOHA is a version of slotted ALOHA, where the contention period consists of time slots with equal lengths. The length of each time slot is considered to be the same as the time needed for a user message to be transmitted to the BS over the channel. The users are synchronized on the basis of the start and end of the time slots. The BS indicates the start of a contention period by sending a message to the users.

We assume that there are U users in a network always having packets ready for transmission to the base station (BS). Out of this U users, N users have fine channel conditions[2] sufficient for a packet transmission. We consider that the network environment has a stable condition regarding fading and shadowing during a contention period, so that all of the N users remain in the contending group of users during a contention period.

In frameless ALOHA users transmit their messages with the same probability of access P_{All}, in all time slots. We denote the number of time slots in a contention period by M. We assume that all the replicas of a user message in a contention period, contain pointers to the other replicas in that contention period, which is required for SIC execution.

Assume that user u_i wants to send its message, named X_i, to the BS in a contention period. The BS received signal in time slot m of the contention period, denoted as Y_m, can be modeled as[3]:

$$Y_m = \sum_{i=1}^{N} s(i,m) X_i \quad 1 \leq m \leq M, \tag{2.12}$$

[2]In this thesis we consider that the BS knows N perfectly at the start of a contention period.

[3]We ignore the noise and distortion that happens through transmissions over the channel.

where $s(i,m)$ is a parameter indicating whether a transmission is occurred by user u_i in time slot m or not, i.e. $s(i,m) = 1$ if transmission has occurred and $s(i,m) = 0$ if it has not. Also,

$$p[s(i,m) = 1] = p(i,m) \; 1 \leq i \leq N, \, 1 \leq m \leq M, \tag{2.13}$$

where $p(i,m)$ indicates the access probability of u_i in time slot m. In this frameless slotted ALOHA, which we refer to as original frameless scheme in this thesis, probability of access is the same for all the users and in all the time slots, and is equal to P_{All}, as mentioned before. However, we will change this to achieve our desired energy efficiency, which will be discussed later in Chapter 4.

After users messages are sent, each arbitrary time slot has one of the following statuses: a) no transmission (idle slot), b) only one transmission (singleton slot), c) more than one transmission (collision slot). Unlike framed slotted ALOHA, the number of time slots in a contention period, M, is not a priori determined in frameless ALOHA. Therefore, users continue their transmissions until they receive a message from the BS notifying them about the end of the frame. Through the ending message sent from the BS, users are also informed whether their message has been resolved by the BS or not. The users whose messages have not been resolved in a contention period, struggle to send their message in the coming contention period.

As discussed in [20], by exploiting SIC at the BS to resolve some of the collisions, and careful design of a stopping criterion, frameless ALOHA achieves significant throughput improvement. In the following, we briefly review the stopping criterion used in this protocol.

Before explaining the stopping criterion, we present some definitions needed to be introduced in this regard.

The instantaneous throughput at time slot m, $T_{\mathrm{I}}(m)$ represents the ratio of the number of resolved users until a given time slot m, i.e. $N_{\mathrm{R}}(m)$, over the number of elapsed time slots:

$$T_{\mathrm{I}}(m) = \frac{N_{\mathrm{R}}(m)}{m}. \tag{2.14}$$

So, at the end of a contention period the throughput, T is equal to $T_{\mathrm{I}}(M)$.

Also, we define the fraction of resolved users at time slot m, $F_{\mathrm{R}}(m)$, as the ratio of the number of resolved users until that time slot, $N_{\mathrm{R}}(m)$, over the number of contending users, N:

$$F_{\mathrm{R}}(m) = \frac{N_{\mathrm{R}}(m)}{N}. \tag{2.15}$$

So, the fraction of resolved users at the end of a contention period, i.e. $F_{\mathrm{R}} = F_{\mathrm{R}}(M)$.

Next, we explain the stopping criterion at the BS, based on which the BS decides to end a contention period.

2.1.6.2 Stopping criteria

Resolving the entire number of contending users messages in a single contention period requires a long period, which leads to a low throughput. Based on analytical and numerical evaluations, the authors in [20] have found thresholds for the fraction of resolved users F_{R} and throughput T, that leads to maximum achievable throughput.

And-or-tree evaluations [21] of frameless slotted ALOHA in [19], shows that $T_{\mathrm{I}}(m)$ and $F_{\mathrm{R}}(m)$ both have an avalanche behavior versus the number of elapsed time slots. This is due to the SIC resolution method where suddenly a large number of users messages get resolved by adding a single equation[4]. This avalanche behavior leads the instantaneous throughput and the fraction

[4]This is similar to what happens in iterative BP decoding [22].

of resolved users to have a sudden jump from a low value to a much higher value after a single time slot. The avalanche point gives the possible maximum throughput.

In [20], it is shown that if we run the simulations for frameless slotted ALOHA and observe the average behavior of $T_{\mathrm{I}}(m)$ and $F_{\mathrm{R}}(m)$, the avalanche point interestingly happens at the same time slot for both. However, the exact behavior of $F_{\mathrm{R}}(m)$ and $T_{\mathrm{I}}(m)$ are not the same. $T_{\mathrm{I}}(m)$ faces local maximums, while $F_{\mathrm{R}}(m)$ shows a more stable performance and increases monotonically before the avalanche point.

Simulation analysis in [20], also shows that the instantaneous throughput has a more complicated behavior. It is sometimes probable that the users transmissions happen in a way that lead to an instant throughput, $T_{\mathrm{I}}(m) = 1$. While on the other hand $F_{\mathrm{R}}(m)$ is still a small value. Thus, in order to achieve the largest possible throughput in a contention period, the authors of [19] have decided that the BS should terminate a contention period either when the fraction of resolved users has reached the desired threshold, i.e.avalanche point F_{opt}, or when the instantaneous throughput has reached to 1. Both these criteria leads to the maximum instantaneous throughput.

To ensure the maximum throughput, F_{opt} is found through heuristic optimizations for different values of N as discussed in [20].

In the following, we go over some of the recent works considering throughput improvement for heterogeneous wireless networks, and also energy efficiency improvement in random access strategies for wireless communication networks.

2.2 Literature Review

This section reviews some of the previous works regarding different random access strategies that are applied in heterogeneous networks, and also consideration of energy efficiency in different random access strategies.

2.2.1 Random Access in Heterogeneous Networks

[23] has provided a saturation throughput analysis for slotted ALOHA protocols used in Wireless Body Area Networks(WBANs). WBANs are considered in IEEE 802.15.6 standard, which provides a specific slotted ALOHA protocol for heterogeneous networks with different user priorities. Saturation throughput shows the maximum load that can be carried by the system in stable conditions.

[24] proposes a new medium access method derived from CSMA/CA according to distributed strategy update mechanism to achieve the Nash equilibrium of random access game. The authors of this paper provide a general framework for modeling a large class of system wide QoS models via the specification of per-node utility functions, in which system wide fairness or service differentiation can be achieved in a distributed manner.

[25] considers a heterogeneous group of independent users sharing their transmission channel via slotted ALOHA protocol. Each user selects a desired throughput, depending on its required QoS and willingness to pay. Users participate in a game where they adjust their probability of transmission to achieve their desired throughput. This paper studies the possible equilibrium points that may be reached by such a network.

[26] models the stability of a network with heterogeneous users in a slotted ALOHA framework. It models the heterogeneous users by dividing the total user population into groups of homogeneous users. The behavior of the system is represented by state equations.

The most recent work in this regard is [27]. This work considers a network with different importance classes who compete for a common channel. It provides a framework for the optimization of transmission strategies, and allowable traffic loads of different classes of this kind of network. Transmission strategy in this work is based on framed slotted ALOHA with SIC, and different classes would have different distributions, over their number of replications of their messages in a frame. In this paper, utility functions are non-decreasing functions of the number of resolved messages from different classes at the BS, and different classes have different utility functions. The optimization goal is to find the distribution functions, and also allowable traffic loads for different classes, so that the overall utility function is maximized. The overall utility function is a weighted summation of the utility functions of all the classes. In fact, this paper is intended to find the best resource allocation to achieve the maximum overall utility function. It is developed based on [12], which considers only one class of users. [12] will be explained later in Section 2.1.5. Our third method of transmission is also based on [12], but there are critical differences between our scheme, and [27] which will be elaborated in Section 3.4.

Our work regarding random access in heterogeneous networks is different from the previous works in several ways. We consider framed slotted ALOHA protocol, and we find the best possible throughput region for a network having several different classes of users. The number of users in each class is also considered to be fixed in our scheme[5]. The differences between our work on heterogeneous random access and existing results are elaborated in Chapter 3.

2.2.2 Energy Efficiency and Random Access Strategies

Energy efficiency of a system can be improved considering different aspects from hardware battery and antenna design to communication and access strategy. In this work, we consider slotted ALOHA access, and we improve its energy efficiency by modifying the access strategy. As mentioned earlier, slotted ALOHA has several real-life applications, for example, in M2M communications. In the following, we review some of the works regarding energy efficiency in different wireless communication networks. In the first section we review the general works that have recently been done, not necessarily on slotted ALOHA random access, and in the second section we focus on the recent works on energy

[5]The words group, and class are used in this chapter interchangeably.

efficiency in slotted ALOHA random access protocols.

2.2.2.1 Works on Energy Efficiency of Access Strategies

In this section we explain some of the general works on the energy efficiency of wireless communication networks from access layer point of view. As previously mentioned there are plenty of works on energy efficiency of WSNs, RFID networks, and some other wireless networks where energy efficiency is a matter of concern. So, we review some of the works with respect to the energy efficiency of these systems below.

WSNs have to sense the environment, process the data they have received, and communicate that data with a base station. Energy efficient protocols in each of theses tasks can have a dramatic impact on the lifetime of these networks. As the scope of this thesis is mainly on the data communication aspect of WSNs, we mention some of the works in this regard. Several efforts have been made to improve the efficiency of access to the shared medium in WSNs. Among them [28], and [29] have proposed a new MAC protocol that helps the energy efficiency in WSNs.

In RFID networks, users access a shared medium to communicate their information to a BS. Most of the works regarding energy efficiency in RFID networks, are performed to find ways to do the information gathering and tag identification process in a more efficient way. In this regard, [30], and [31] propose cardinality estimation methods for large scale and dynamic RFID systems that help to prevent waste of time and energy in the process of tag identification. [32] has introduced a cooperative, distributed reader collision avoidance algorithm suitable for energy efficient wireless mobile network environments cooperated with RFID. [33] has proposed an energy aware anti-collision protocol based binary search tree for RFID identifications. In [34] the authors have attempted to design efficient polling protocols to collect real-time information from a subset of tags in a large RFID system. [34] proposes an information collection protocol that is able to reduce per tag energy consumption significantly, however, at the cost of longer execution time. [35, 36] propose new MAC layer collision-arbitration protocols suitable for dynamic and large-scale RFID networks with power consumption.

There are some other wireless communication networks where energy efficiency is of vital importance, for instance wireless body area Networks (WBANs) need to be designed in an efficient way as in these kinds of devices battery size is often small and specially if they are implanted in the body, it is rarely possible to change them. [37] evaluates the energy efficiency of proposed MAC protocols for WBANs.

The following section particularly considers energy efficiency that is applied to slotted ALOHA random access protocol in the context of wireless communication networks.

2.2.2.2 Works on Energy Efficiency Considering slotted ALOHA Random Access

Energy efficiency in random access protocols is of particular interest, especially in some wireless M2M communication contexts, for example "active" RFID identification networks and WSNs.

RFID networks have recently found so many of their applications in our everyday lives. The modern RFID ubiquitous sensing and identification requires high throughput and at the same time low energy consumption. There are several works on the energy efficiency of random access protocols in RFID identification networks. As the main focus of this thesis is on the slotted ALOHA random access scheme, in this section we introduce some of the works regarding energy efficiency of RFID networks using slotted ALOHA protocol.

[38] has compared different RFID anti-collision pure and Slotted ALOHA protocols based on their energy efficiency, and the same authors have studied the energy issue for RFID networks with Framed slotted ALOHA based anti-

collision protocols in [39]. [40] proposes a new tag identification approach, Tree Slotted ALOHA, to reduce the number of transmission collisions, and thus energy consumption. The authors in [41] have attempted to find an optimized frame size for the non-muting version of the Basic Framed slotted ALOHA collision resolution protocol in RFID networks, which brings energy efficiency to the scheme.

In addition to the works on the energy efficiency of slotted ALOHA random access in RFID networks, several works have developed techniques to improve energy efficiency of slotted ALOHA random access in the context of WSNs with an ad hoc fashion. Among them [42] shows that in slotted ALOHA protocol, optimizing the users transmission probability helps to enhance the network energy efficiency. In another attempt to improve the energy efficiency of slotted ALOHA random access, [43] draws a comparison between energy efficiency of the single-power-level slotted ALOHA scheme and the multiple-power-level one, and shows that single-power-level slotted ALOHA results in both higher throughput and higher energy efficiency.

As far as we know there is no recent attempt on the improvement of energy efficiency in any version of the SIC enabled slotted ALOHA random access protocols, especially frameless slotted ALOHA random access with the highest throughput. In random systems with no previous plan for the tasks that should be done, there is always a trade off between the concerned energy efficiency, and the time needed for the tasks to be done. In this work, we consider optimization of both these factors to achieve the highest throughput reported in the literature, while at the same time we try to reduce the energy consumption.

Chapter 3

Multi Class Framed Slotted ALOHA

Many wireless networks consist of groups of users with different priority, quality of service (QoS), or constraint on energy consumption. Different groups may have different desired throughput goals, according to their QoS, power consumption concerns, and many other factors. To give a practical example, consider WBANs. In WBANs the group of sensors monitoring a patient's heart rate play a more critical role in showing the vital signals than the group of sensors presenting the blood sugar level, so the first group of sensors need to have a higher throughput. As another practical example, we can consider a group of satellites in the space, which are different in terms of their priority to have access to a shared medium. In this part of this thesis, we discuss transmission policies that help different groups achieve their throughput goals.

In Section 2.2.1, we explained some previous works regarding non-homogeneous networks in the literature. In the following, we briefly review a work closely related to our contributions.

The authors of [27] consider a network with different priority classes competing for a common medium. They provide a framework for the optimization of transmission strategies, and also allowable traffic loads of different classes in such a network. Transmission strategy in this work is based on framed slotted ALOHA with SIC, and different classes will have different distribution functions over the repetition of their messages in a frame. In this paper, utility functions are non-decreasing functions of the number of resolved messages from different classes at the BS, where each class has a different utility function. The optimization goal is to find distribution functions, and also suitable traffic loads for different classes, so that the overall utility function is maximized. The overall utility function is a weighted summation of the utility functions of all classes. In fact, [27] is intended to find the best resource allocation to achieve the maximum overall utility function. It is developed based on [12], which considers only one class of users. [12] is previously explained in Section 2.1.5 in details. It is briefly reviewed in Section 3.4 of this chapter, as our third method of transmission is also based on [12]. There are critical differences between our scheme, and [27] which will be elaborated in Section 3.5.

3.1 System Model

In this section, first we define our framework, and then we explain our three proposed methods of transmission.

We assume a network consisting of N users, in k classes with different priorities. We denote the set of classes by $\{C_1, C_2, ..., C_k\}$, where C_n denotes the nth class. Class C_n has N_n number of users, and $N_1 + N_2 + ... + N_k = N$. We also assume N time slots in a frame. In all our methods of transmission, we consider framed slotted ALOHA as the random access protocol. We examine two different versions of framed slotted ALOHA protocol: (i) without SIC which is discussed in Section 3.2, (ii) and SIC enabled discussed in Sections 3.3, and 3.4.2.

The number of resolved users from each of the classes of users at the BS divided by the number of time slots in a frame is defined as the throughput of that class of users. If we denote the number of resolved users from an arbitrary class, C_n as R_n, the corresponding throughput of this class will be denoted by T_n, and it is $T_n = \frac{R_n}{N}$. We define $(T_1, T_2, ..., T_k)$ a throughput k-tuple, meaning that Class 1 has throughput T_1, Class 2 has throughput T_2, and so on. A throughput k-tuple is called achievable if there exists a transmission strategy that achieves the throughput k-tuple. The set of all achievable throughput k-tuples forms a throughput region, where all points in the region correspond to achievable throughput k-tuples. Basically, throughput region is a region made by throughput axes of different classes and a boundary condition forced by the method of transmission. This region is an area in the case of a network with two classes, and a volume in the case of a network with three classes, and its dimension goes higher as the number of classes increase.

In the following sections, we explain each of the three framed slotted ALOHA transmission protocols that we have examined. In each section, we bring the simulation results, and also the related analysis. Finally, we compare all methods.

3.2 Framed Slotted ALOHA with No SIC

We have explained the framed slotted ALOHA in Chapters 1, and 2 of this thesis. Here, we want to expand that idea to a network with k classes of users, who are contending to transmit their data in the slots of a frame. As mentioned before, there are N time slots in a frame, and N_n users in an arbitrary class C_n, where $N_1 + N_2 ... + N_k = N$. In a specific frame, each of the users from C_n has a message to transmit with probability p_n. Exactly the same as the framed slotted ALOHA with one group of users, in this scheme the BS is only able to resolve messages that has been received in singleton slots. As mentioned before, we denote the number of resolved users from C_n by R_n. Thus, we define throughput for C_n, i.e., T_n, as $T_n = \frac{R_n}{N}$.

Formula for the throughput of an arbitrary class C_n, when this kind of transmission policy is applied to a network with k classes of users is intuitive to derive, as presented in the following equation:

$$T_n = N_n \frac{p_n}{N}(1 - \frac{p_n}{N})^{(N_n - 1)} \prod_{j \in \{1,\ldots,k\}, j \neq n} (1 - \frac{p_j}{N})^{N_j} \tag{3.1}$$

We now find the best throughput region for this setup. To do this, one can fix $k-1$ entry of the throughput k-tuple, and maximize the one remaining entry. This can be repeated for all points of the k-dimensional space to find the throughput region. So, we can define our optimization problem as the following:

$$\begin{aligned} & \forall i \in \{1, ..., k\} \\ & \max_{\{p_1,\ldots,p_k\}} \quad && T_i \\ & \text{s.t.} && T_j \geq x_j \geq 0. \quad \forall j \neq i \end{aligned} \tag{3.2}$$

In the above equation, x_j, $\forall j \neq i$ indicates the required limitation that will be forced on other users than the specific user u_i. By sweeping over all the possible values for x_j, $\forall j \neq i$, and finding the maximum T_i we are able to find the best throughput region. However, as this approach seems impractical, we can find this throughput region by performing a grid search over all the access probabilities, i.e., $\{p_1, \ldots, p_k\}$ and finding the throughput boundary that is created by them when the above mentioned method of access is applied.

For $k = 2$, and $N = 100$, for two cases when $N_1 = N_2 = \frac{N}{2}$, and also when $N_1 = \frac{N}{4}$, and $N_2 = \frac{3N}{4}$ we have performed this grid search based on our analysis presented in (3.1). To verify our analysis, we have also repeated the optimization using computer simulation instead of (3.1). For this, we run the simulations 1000 times, and we have presented the average throughput region. The grid search in all of the optimizations is done over $p_1, p_2 \in [0, 1]$ with step size of 0.02. The following figures show this optimization by using the formula, and simulation for $N = 100$, and $N_1 = N_2 = N/2$, and also $N_1 = \frac{N}{4}$, and $N_2 = \frac{3N}{4}$ respectively. As it can be observed the result of optimizations based on the formula exactly matches the result of optimization based on the simulation of the scheme.

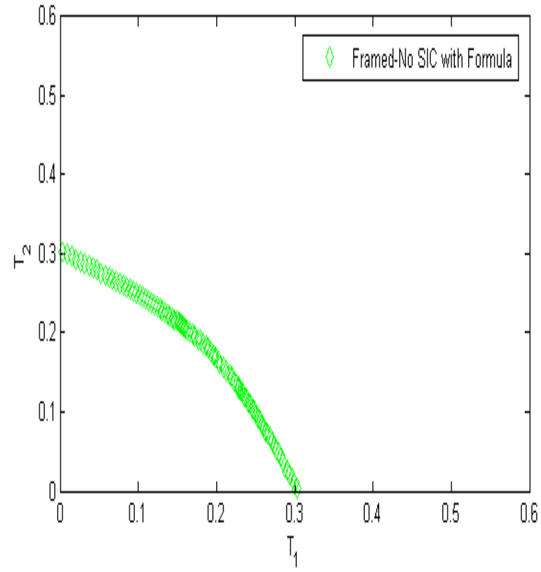

Figure 3.1: Framed slotted ALOHA with no SIC, with formula, $N = 100$, $N_1 = N_2 = \frac{N}{2}$.

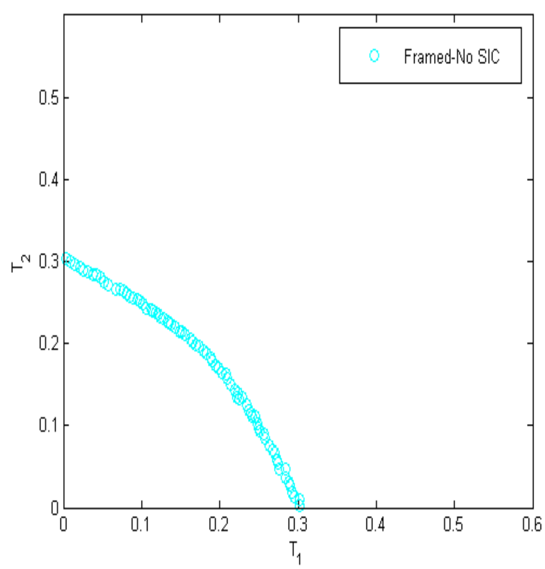

Figure 3.2: Framed slotted ALOHA with no SIC, with simulation, $N = 100$, $N_1 = N_2 = \frac{N}{2}$.

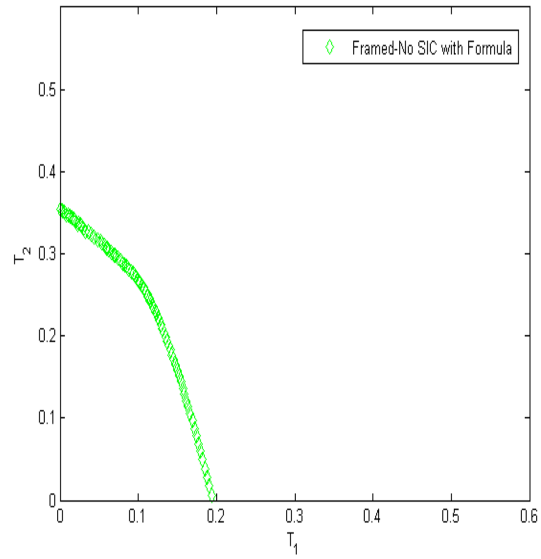

Figure 3.3: Framed slotted ALOHA with no SIC, with formula, $N = 100$, $N_1 = \frac{N}{4}, N_2 = \frac{3N}{4}$.

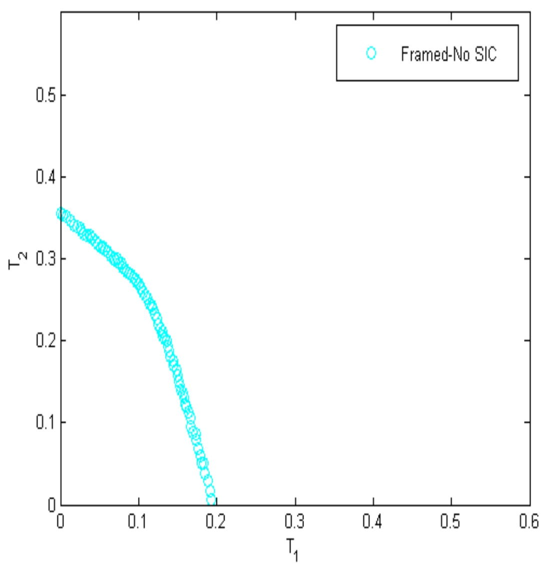

Figure 3.4: Framed slotted ALOHA with no SIC, with simulation, $N = 100$, $N_1 = \frac{N}{4}, N_2 = \frac{3N}{4}$.

In the following sections, we will test schemes in which users of different classes send more than one replica of their messages in a frame. In order to resolve collisions and increase throughputs corresponding to each of the classes, we consider that the BS uses SIC.

3.3 Framed Slotted ALOHA with Regular Repetition and SIC

In this section, we introduce another method of transmission in framed slotted ALOHA for a setup with N users in k different classes, having their transmissions in a frame with N time slots. We consider that each of the users from a specific class, C_n, transmits its message in a specific frame with probability p_n, and if it is intended to have a transmission in that frame, it transmits $l_n \leq N$ replicas of its message in l_n randomly and uniformly chosen time slots of the frame. Due to the fact that all the users in the same class transmit the same number of replicas of their messages in a frame, this method is also referred to as regular repetitions, we will see the irregular repetition method in the next section.

We consider that this scheme is SIC enabled, meaning that the BS utilizes collisions to recover messages. In SIC, when the BS has received all the transmissions in the time slots of a frame, it tries to find time slots with only one transmission in them, i.e., singleton slots. Then the BS tries to cancel the interference caused by these recovered messages from all the time slots of the frame. This interference cancellation leads to some other singletons. The BS can repeat the procedure until either there is no more singleton, or all the users messages are recovered.

Our goal is to find the best throughput region for different classes of users in a network where regular repetition with SIC is applied in all the classes.

An easy solution that comes to mind for this setup is that for each individual class, C_n we find the best set of l_n, and p_n that leads to the maximum throughput $T_{n\mathrm{MAX}}$ when that class is the only group whose users are transmitting in the frames, and then using time sharing we assign different percentages of time to different classes in a way that we reach to our desired set of k-tuples of throughputs over all the classes. For example, if we let $x_n\%$ of all available time slots to the users in class C_n, where these users transmit with their optimum values for p_n, and l_n then they would reach to $x_n\%$ of their maximum throughput when they were alone, i.e., $t_n = \frac{x_n}{100} T_{n\text{MAX}}$. The achievable throughput boundary using time sharing would have k-tuple points $(t_1, t_2, \dots, t_k)$, such that $\frac{T_1}{T_{1\text{MAX}}} + \dots + \frac{T_k}{T_{1\text{MAX}}} = 1$. However, we will show that optimization over p_i, and l_i outperforms time sharing. That is, by performing a grid search over $\{p_1, \dots, p_k\}$ in the range $[0, 1]$, and $\{l_1, \dots, l_k\}$ all in range 1 to $l_{\max}$, and finding the largest boundary, we can achieve a larger throughput region than the one achieved by time sharing. We have presented the results corresponding to time sharing and also optimization via search for two setups, when $k = 2$, and $N = 100$: (i)$N_1 = N_2 = \frac{N}{2}$, and (ii) $N_1 = \frac{N}{4}$, and $N_2 = \frac{3N}{4}$ in the following two figures, respectively.

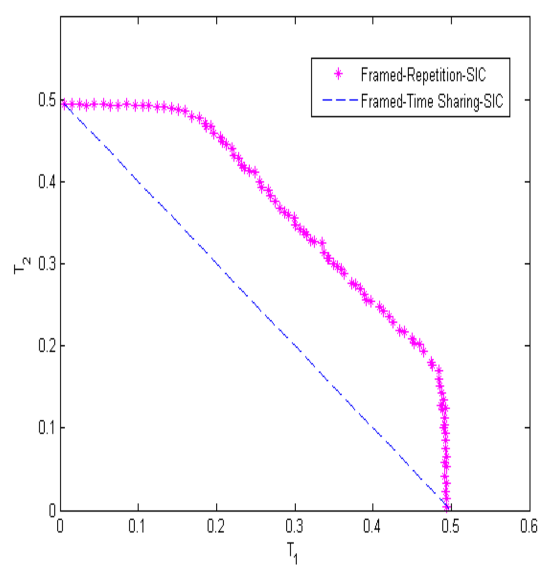

Figure 3.5: Framed slotted ALOHA with repetition and SIC, accompanied by the results for time sharing, for $N = 100, N_1 = N_2 = \frac{N}{2}$.

For both the time sharing approach and the search approach, we do the optimizations over the variables of the schemes, i.e., p_1, p_2, l_1, and l_2. To this end, we searched $p_1, p_2 \in [0, 1]$ with step size 0.02, and $l_1, l_2 \in \{1, 2, 3\}$[1]. All the simulations are performed 1000 times, and we present the average throughput of each of the classes as the result.

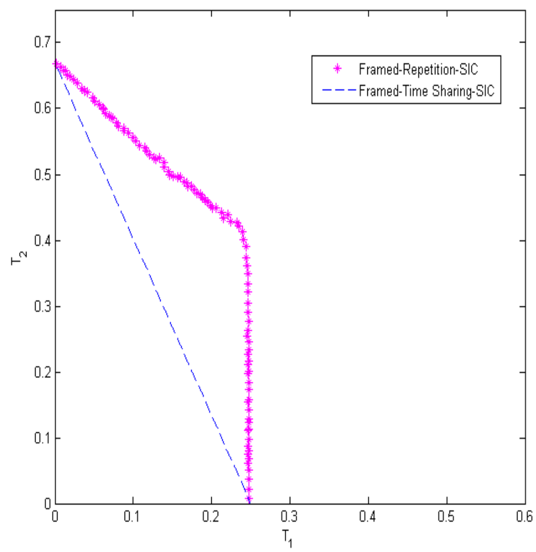

Figure 3.6: Framed slotted ALOHA with repetition and SIC, accompanied by the results for time sharing, for $N = 100, N_1 = \frac{N}{4}, N_2 = \frac{3N}{4}$.

The achievable region for framed slotted ALOHA with repetition can be analytically derived. However, we delay this discussion to the next section, where we consider a more general transmission protocol, i.e., irregular repetition, for which we find the achievable region analytically.

[1] Our search on these values for the number of repetitions is due to the fact that we did not observe further improvement by increasing the number of repetitions even in a setup with 1 class of networks, C_1, and $N_1 < N$ users.

3.4 Framed Slotted ALOHA with Irregular Repetition and SIC

In this section, we introduce our last and best method of transmission for N users in k different classes transmitting their messages in N time slots. In this method the same as the previous method, we consider that users who are intended to have transmissions in a frame, transmit their messages replicas more than once randomly in the frame, and SIC is also applied. However, contrary to the previous method, we introduce special sets of distributions over the number of replicas of messages sent by users of different classes. As the number of replicas of messages transmitted by all the users of the same class are not the same in this method, it is referred to as irregular repetition with SIC. Similar to the two previous sections, i.e., framed slotted ALOHA without SIC, and framed slotted ALOHA with regular repetition and SIC, here we want to find the best sets of distributions that lead to the largest possible throughput region.

Our work in this section is based on [12]. As discussed in 2.1.5, [12] has worked on framed slotted ALOHA with irregular repetition, and SIC in the context of one class of users. It considers that there are N users in a network, and N time slots in a frame. Also, it assumes that out of this number of users only m users are allowed to transmit their messages in a frame. So, the traffic load is $G = \frac{m}{N}$. The m users who are about to transmit their messages will have a distribution for their number of replicas to be sent in a frame. The polynomial representation of this probability distribution function is defined as, $\Lambda(x) \triangleq \sum_{l=1}^{N} \Lambda_l x^l$, where Λ_l indicates the probability that a user has l replicas of its message in a frame. In this paper, Liva has shown that for each distribution assigned on the m transmitting users, there is a threshold for G, as G^* up to which the probability of failure in message recovery is negligible, and thus the best throughput is equal to G^*. Liva has provided a framework for optimization of the irregular repetition, $\Lambda(x)$, in order to reach to a maximum threshold for G, i.e., G^*. Simulation results show that by setting the maximum number of repetitions to 8, distribution $\Lambda(x) = 0.5x^2+0.28x^3+0.22x^8$, will give $G^* = 0.938$, asymptotically when N tends to infinity. In the following, we will use distribution $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$ to develop our third method of transmission. If we examine this distribution in an actual scheme with not a very large N, we can find the actual G^*, and its corresponding T^* by observing the throughput versus load plot for that specific N. In the remainder of this chapter, G^* and T^* indicate the actual threshold for the traffic load, and its corresponding throughput. An example of the plot of throughput versus traffic load for $N = 100$ is shown in the following figure. For $N = 100$, $G^* = 0.74$, and $T^* = 0.68$.

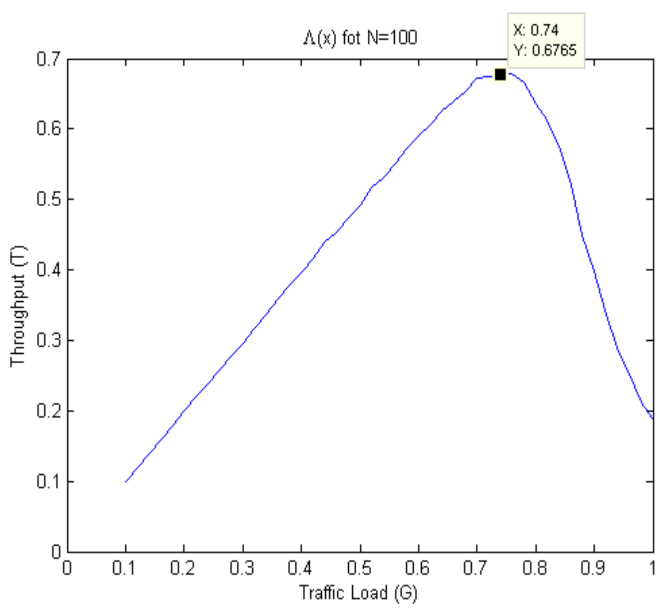

Figure 3.7: Throughput versus traffic load, when $\Lambda(x)$ is applied for $N = 100$.

In the following, first we find the best achievable throughput region, and then we explain how to achieve this region.

3.4.1 Throughput Region

In a network with total N users in k classes, where irregular repetition in N time slots accompanied by SIC is applied, the highest throughput achieved by an arbitrary class of users, C_n, would be $T_n = \min\{\frac{N_n}{N}, T^*\}$. The reason for this value as the highest throughput for a specific class, C_n, is that there are two possible cases that may happen. Case 1: $N_n < T^*N$, where successful transmission of all users in this class is possible by activating all the users from C_n, and also probably some users from other classes, up to the point that G^*N users are only active. So, in this case we will have $T_n = \frac{N_n}{N}$. Case 2: $N_n > T^*N$, where $T_n = T^*$ is achievable, if we turn all the users from other classes and also some of the users from C_n off, in order to satisfy the condition that at most G^*N users should be active. This way T^*N users from C_n will be successfully resolved, or $T_n = T^*$. This $T_n = \min\{\frac{N_n}{N}, T^*\}$ indicates a point on the T_n axis, when all the users from other classes are off. So, the boundary $T_n = \min\{\frac{N_n}{N}, T^*\}$, can be obtained when all the users from class C_n, plus between 0 to $G^*N - N_n$ users from other classes are actively having transmissions. Furthermore, we know that by applying the best distribution the highest total throughput that can be achieved by the whole k classes of users is T^*, which means that $T_1 + T_2 + ... + T_k = T^*$ is the boundary of the best throughput region. We know that this boundary is obtained when G^* users are active in the network. So, this throughput region consists of $k+1$ boundaries, i.e.,

$$\begin{cases} T_i = \min\{\frac{N_i}{N}, T^*\} & \text{for } 1 \leq i \leq k \\ T_1 + T_2 + ... + T_k = T^*. \end{cases}$$

In this region, for $1 \leq i \leq k$, the boundaries $T_i = \min\{\frac{N_i}{N}, T^*\}$ are easy to reach, as discussed above. So, the primary boundary to discuss how to reach is $T_1 + T_2 + ... + T_k = T^*$. In fact Achieving the boundaries is equal to achieving the whole region. This is due to the fact that the inner area contains points of k-tuple throughputs for the k classes, which have at least one class with a lower throughput than the points on the boundary. Thus, the inner area is easily achievable by having some users from the specific classes with lower throughputs than the boundary points not to transmit.

We have presented the throughput region for $N = 100$, $k = 2$, when (i) $N_1 = N_2 = \frac{N}{2}$, and (ii) $N_1 = \frac{N}{4}$, $N_2 = \frac{3N}{4}$, in Figures 3.8, and 3.9, respectively. For case (i), this throughput region consists of three lines, $T_1 = 0.5$, $T_2 = 0.5$, and $T_1 + T_2 = 0.68$, and for (ii), it consists of $T_1 = 0.25$, $T_2 = 0.68$, and $T_1 + T_2 = 0.68$.

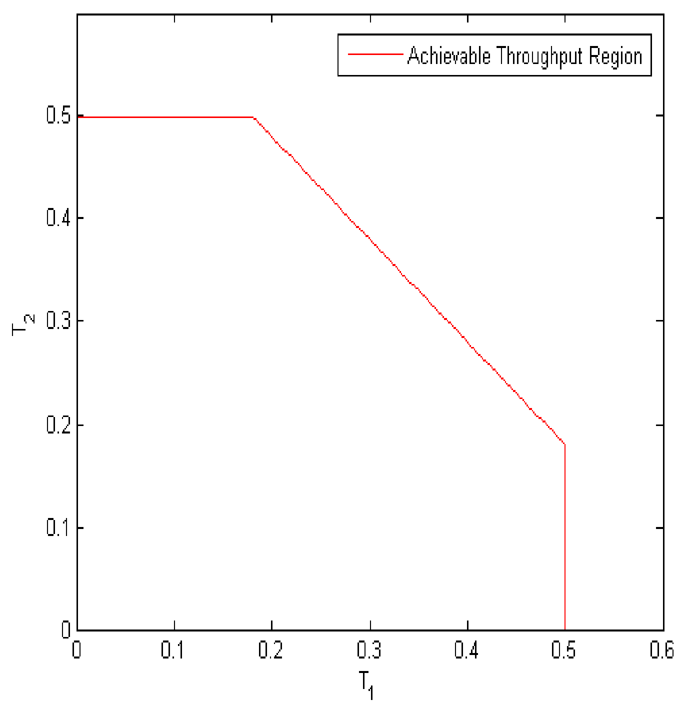

Figure 3.8: Achievable throughput region for $N = 100$, $N_1 = N_2 = \frac{N}{2}$.

The boundary $T_1 + T_2 + ... + T_k = T^*$ is achievable by selectively making the users of different classes on and off. The details are explained in the following section.

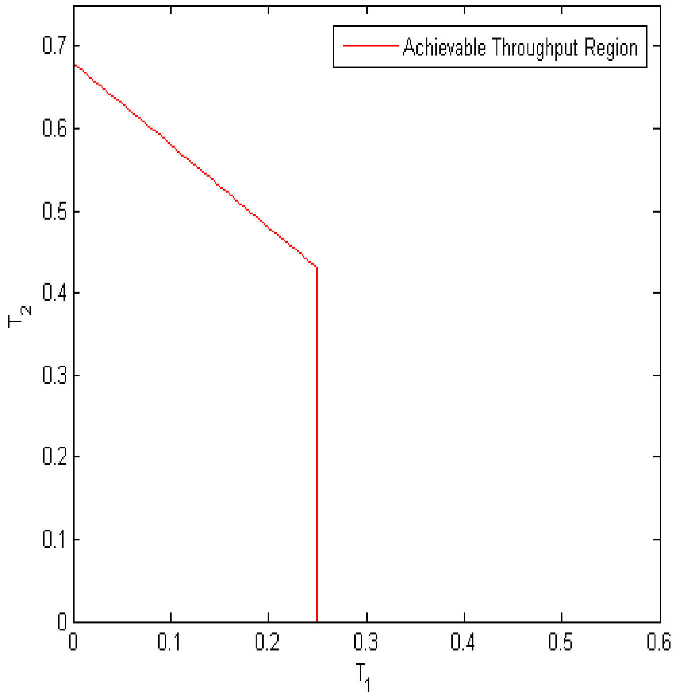

Figure 3.9: Achievable throughput region for $N = 100$, $N_1 = \frac{N}{4}, N_2 = \frac{3N}{4}$.

3.4.2 Selective On/Off Approach

As mentioned before, for $1 \leq i \leq k$ the $T_i = \min\{\frac{N_i}{N}, T^*\}$ boundaries in the throughput region are easy to reach, so our goal in this section is to explain our proposed method to achieve the $T_1 + T_2 + ... + T_k = T^*$ boundary. We want to find the set of distributions that should be assigned to the k different classes of users so that this primary boundary is achieved.

As discussed before, from [12], we have the best distribution $\Lambda(x)$ over the users replicas, and also its corresponding G^*, and T^*. With k classes of users, initially it seems that one need to optimize k different degree distributions one for each class to achieve the boundary of the throughput region. As we discuss below, a much easier solution can be formed. To see how, notice that when k classes of users transmit with degree distributions $\Lambda_1(x)$ to $\Lambda_k(x)$ respectively, from the time slot point of view, the situation is the same as when all users transmit with the weighted average of these degree distributions. The overall distribution would be $\sum_{i=1}^{k} \frac{N_i \Lambda_i(x)}{N} = 1 - G^* + G^* \Lambda(x)$, which means to have $G^* N$ active users with distribution $\Lambda(x)$ that leads to the overall throughput T^*. Now since decoding success is entirely affected by the weight distribution on time slots, one can argue that instead of optimizing each $\Lambda_i(x)$, one need to only care about $\Lambda(x)$. Also, finding the $\Lambda(x)$ which results in the maximum throughput is a solved problem [12]. For this, we need to keep $(1 - G^*)$ portion of users silence and use the suggested degree distribution, $\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$ for the rest of users.

The conclusion of the above discussion is that if we want to achieve different points of the boundary $T_1 + T_2 + \ldots + T_k = T^*$, we can simply use degree distributions in the general form $\Lambda_n(x) = (1 - \alpha_n) + \alpha_n \Lambda(x)$, where α_n indicates the portion of users in class C_n that are transmitting. This way, we ensure that the average degree distribution is the optimal $\Lambda(x)$, and with proper choice of α_n for all the k classes, we achieve different points of the boundary $T_1 + T_2 + \ldots + T_k = T*$.

Now, we tend to the problem of finding α_n for a given throughput k-tuple on the boundary. First notice that there should be a constraint on $\{\alpha_1, \alpha_2, ..., \alpha_k\}$, so that the total active users in the network would be equal to $G^* N$, which is $\sum_{i=1}^{k} N_i \alpha_i = G^* N$. This constraint is to only allow $G^* N$ users from the total N users in the network to have transmissions. We know that when $N_n \alpha_n$ users from C_n are active to have transmissions, the corresponding throughput to this class T_n, would be equal to $\frac{N_n \alpha_n T^*}{G^* N}$, which considering the above mentioned constraint would lead to the overall throughput boundary,

$$\sum_{i=1}^{k} T_i = T^*. \tag{3.3}$$

Having this throughput boundary, $T_1 + T_2 + ... + T_k = T^*$, it is easy to come up with distributions that should be assigned to each of the classes to achieve a specific point on it. For instance, to achieve the throughput k-tuple $(T'_1, ..., T'_k)$, for $1 \leq i \leq k$, one should set $\alpha_i = \frac{G^* N T'_i}{N_i}$, and find the corresponding distribution $\Lambda_i(x) = (1 - \alpha_i) + (\alpha_i)\Lambda(x)$.

From $\alpha_i = \frac{G^* N T'_i}{N_i}$, and $G^* < 1$, it is obvious that all $\{\alpha_1, ..., \alpha_k\}$ are strictly less than 1. This has been expected, since they indicate the portion of active users from each of the classes to have transmissions. So, we have shown that our proposed method of access is able to give all the k-tuples on the $T_1 + T_2 + ... + T_k = T^*$ boundary. Also, our simulations, show that the result of using $\Lambda_i(x) = (1 - \alpha_i) + (\alpha_i)\Lambda(x)$ as the distributions over the repetitions in each of the k classes of user, with the condition $\sum_{i=1}^{k} N_i \alpha_i = G^* N$, exactly matches our expectations to reach the $\sum_{i=1}^{k} T_i = T^*$ throughput boundary.

3.5 Comparison

In this section, we compare throughput regions of all our proposed methods of transmissions in this chapter. Results for a network with $N = 100$, $k = 2$, considering two cases of: (i) $N_1 = N_2 = \frac{N}{2}$, and (ii) $N_1 = \frac{N}{4}$, $N_2 = \frac{3N}{4}$ are presented, in Figures 3.10, and 3.11, respectively. These figures show the corresponding results to different versions of framed slotted ALOHA, i.e., with no SIC, with time sharing and SIC, with regular repetition and SIC, and finally, with irregular repetitions and SIC.

As we expected, the best throughput region is shaped by the framed slotted ALOHA method with irregular repetitions and SIC. It can easily be conceived from the figures, that methods accompanied by SIC resolution algorithm are far better than methods that are not. This is basically because SIC helps to resolve collisions, and this way throughputs are enhanced. Also, we can see how the regular repetition, and also irregular repetition have improved the throughput region in comparison to time sharing as an easy solution, while all are using SIC.

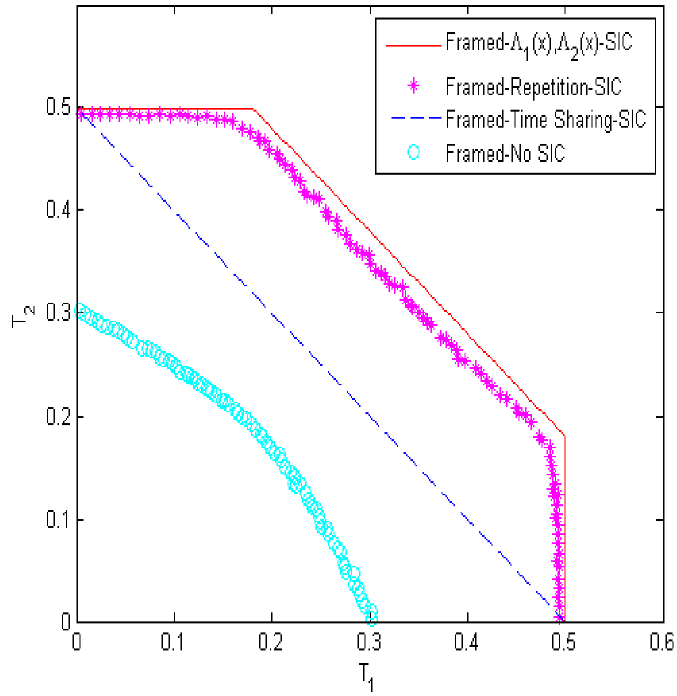

Figure 3.10: Comparing throughput regions of different framed slotted ALOHA methods of transmission for $N = 100$, $N_1 = N_2 = \frac{N}{2}$.

Comparing regular and irregular repetitions, we conceive that there is not very much difference in the performances of regular repetition, presented in purple stars, and irregular repetition, presented in red solid lines. Irregular repetition provides a major improvement over the regular repetition in the process of calculating the distributions that should be assigned to different classes. This is because of the fact that if we want to reach to a point of the throughput boundary, calculation of its corresponding distributions over different classes are so easy to derive. On the other hand, reaching to a point of the throughput boundary from the framed slotted ALOHA with regular repetition needs optimizing different classes probabilities, and also number of repetitions. To compare the regular and irregular repetition methods from energy consumption point of view, we should notice that in the irregular repetition method, for the whole throughput boundary the average energy consumption of the whole users in the network is constant and equal to 2.664[2], while the average energy consumption in the regular repetition method, is different for different points of the resulting boundary. This is a major issue regarding stability of networks in the context of energy, when switching from one pair of throughputs on the boundary to another pair.

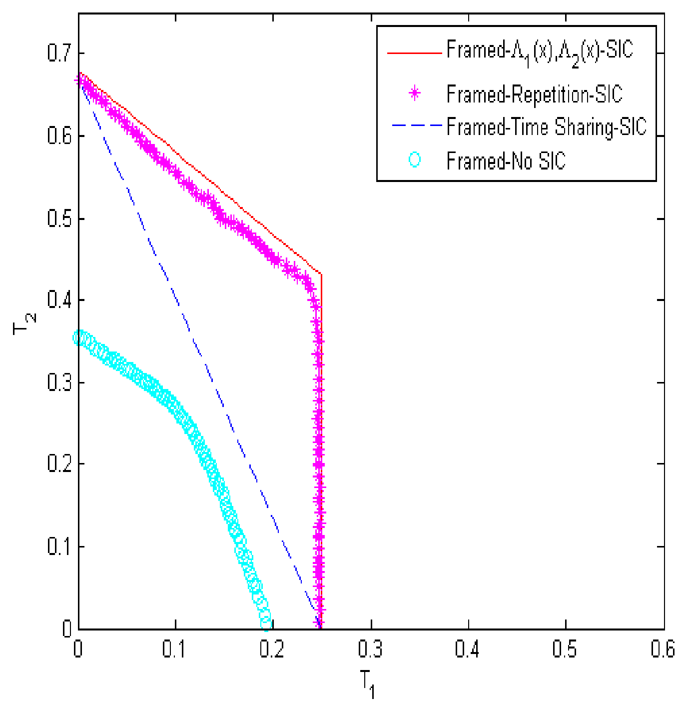

Figure 3.11: Comparing throughput regions of different framed slotted ALOHA methods of transmission for $N = 100$, $N_1 = \frac{N}{4}$, and $N_2 = \frac{3N}{4}$.

Regarding time sharing with SIC, we should say that it does not give a great result, comparing to regular and irregular repetition methods. Time sharing also needs a central coordinator to manage different classes to have their transmission in a desired order, while neither the regular, nor the irregular repetition method needs such a central coordination between different classes, and users of each class perform their transmissions locally.

[2]This comes from the overall distribution, and the overall traffic load threshold, which are $\Lambda(x)$, and G^*.

Chapter 4

Modified Frameless Slotted ALOHA

This chapter presents our contributions, and analysis regarding energy efficiency in frameless slotted ALOHA access protocol. Our work is based on the original frameless ALOHA [20], introduced in Section 2.1.6 of Background.

In the first section of this chapter, we briefly review the necessary concepts from the original frameless ALOHA scheme, and in the second section we explain our two proposed access strategies that help reduce the network energy consumption, while maintaining the same throughput as the original frameless ALOHA. Finally, Section 4.3 presents the simulation results of our different access strategies.

4.1 Original Frameless ALOHA

Aiming at improving the network throughput, in Frameless ALOHA there is not a fixed number of slots in each frame, instead there is a stopping criterion based on the number of resolved messages, and the instantaneous throughput at the BS. The set of time slots in which users are having their transmissions is called a contention period. The BS decides to end a contention period by sending a feedback to the user, when a stopping condition is met. Using a dynamic frame length accompanied by the deployment of SIC at the BS, frameless ALOHA increases the network throughput considerably comparing to the previous versions of ALOHA protocol.

In frameless ALOHA, users are synchronized on the basis of the start and end of a time slots. A contention period consists of equal length time slots. In this original frameless ALOHA, all users transmit their messages with the same probability of access P_{All}, in all time slots. In this chapter, we present our proposed methods of access in which users access probabilities change adaptively. We assume that there are N users with fine channel conditions to transmit their messages, all of which remain in the contending group of users during a contention period. We denote the number of time slots in a contention period by M, which is not a fixed number. We assume BS uses SIC to resolve collisions, when possible.

In the following, we review the stopping criterion used in this protocol, which is the same as the stopping criterion used for our adaptive proposed schemes. Before explaining the stopping criterion, we define the necessary parameters in this regard.

$T_{\text{I}}(m)$ as the instantaneous throughput at time slot m, represents the ratio of the number of resolved users until a given time slot m, i.e., $N_{\text{R}}(m)$, over the number of elapsed time slots:

$$T_{\text{I}}(m) = \frac{N_{\text{R}}(m)}{m}. \tag{4.1}$$

So, throughput at the end of a contention period, T is equal to $T_{\text{I}}(M)$.

Also, $F_{\text{R}}(m)$ as the fraction of resolved users at time slot m is the ratio of the number of resolved users until that time slot, $N_{\text{R}}(m)$, over the number of contending users, N:

$$F_{\text{R}}(m) = \frac{N_{\text{R}}(m)}{N}. \tag{4.2}$$

So, the fraction of resolved users at the end of a contention period, F_{R} is equal to $F_{\mathrm{R}}(M)$.

Analysis on frameless ALOHA, shows that $T_{\mathrm{I}}(m)$ and $F_{\mathrm{R}}(m)$ both have an avalanche behavior versus the number of elapsed time slots [20]. The avalanche point gives the possible maximum throughput. Also simulation analysis, shows that the instantaneous throughput has a more complicated behavior. It is sometimes probable that the users transmissions happen in a way that lead to an instant throughput, $T_{\mathrm{I}}(m) = 1$. While on the other hand $F_{\mathrm{R}}(m)$ is still a small value. Thus, in order to achieve the largest possible throughput in a contention period, the BS should terminate a contention period either when the fraction of resolved users has reached the desired threshold, i.e., avalanche point F_{opt}, or when the instantaneous throughput has reached to 1 [20]. Both these criteria lead to the maximum instantaneous throughput. To ensure the maximum throughput, F_{opt} is found through heuristic optimizations for different values of N. In original frameless ALOHA the optimization goal is to find the available parameters p_{All}, and F_{R} that lead to the maximum throughput. The numerical results corresponding to this scheme is presented in Section 4.3.1. The stopping criteria for our proposed versions of frameless ALOHA are the same as the original frameless ALOHA.

In the following section, we go over our two proposed versions of frameless slotted ALOHA.

4.2 Adaptive Frameless ALOHA

The main contribution of this chapter, i.e., suggesting modified frameless ALOHA schemes that improve the energy efficiency of the original scheme, is elaborated in this section. The highest yet achieved throughput for slotted ALOHA random access in the literature, i.e., in [20], is through the access strategy elaborated in Section 2.1.6, and reviewed in the above section where all the users have the same access probability P_{All} during the whole period of transmission. In this section our aim is to maintain the same throughput as [20], but reduce the average number of transmissions per slot, which translates to a lower energy consumption per slot. We bring this by carefully designing the access probability at the users.

We propose two access strategies, where users access probabilities change over the time slots adaptively. We will present the two access strategies accompanying their related analysis in the two following subsections. Further, their related simulation results come in Section 4.3. The results show that both our proposed schemes help reduce the average number of transmissions per slot for the small and medium sized network of users, i.e., $25 \leq N \leq 200$.

The same as Chapter 2, we denote the access probability of user u_i at time slot m by $p(i, m)$. In both our proposed schemes, at the start of a contention period the BS sends the users a message indicating the start of a contention period, as well as their initial access probability p_{init}. Thus,

$$p(i, 1) = p_{\text{init}}, \ 1 \leq i \leq N. \tag{4.3}$$

All the users will be assigned the same initial access probability, based on the BS's estimation of the number of contending users N in a contention period. This initial access probability is found through optimizations elaborated later, in this chapter.

As the users progress in transmission through the slots of a contention period, $p(i, m)$ changes adaptively by user u_i. If the user had a transmission in the current time slot, it reduces its access probability for the next time slot. Also, if the user did not have a transmission in the current time slot, it increases its access probability for the next time slot. The intuition behind this approach is to increase the chance of successful transmission for the users that have not transmitted before the current time slot by reducing the chance of collision from the users that already have transmitted. Note that for this to happen, the increase step should be smaller than the decrease step. This is to avoid lots of users having high access probabilities, and thus to lower the number of collisions.

The difference between our two proposed access strategies is in the decreasing and increasing steps. In the first adaptive strategy the steps are constant over the time slots, but in the second one the steps change adaptively too. We explain this in more details in the following.

4.2.1 Adaptive Change with Constant Parameters

In this scheme, for simplicity, we assume that the increase and decrease steps at all the users and in all the time slots are α and αk, respectively, where k is a positive integer. That said, the access probability of the users is updated as follows:

$$p(i, m+1) = \begin{cases} p(i, m) - \alpha k, & \text{if } s(i, m) = 1, \\ p(i, m) + \alpha, & \text{if } s(i, m) = 0. \end{cases} \tag{4.4}$$

In (4.4), $s(i, m)$ is a parameter indicating whether a transmission is occurred by user u_i in time slot m or not, i.e., $s(i, m) = 1$ if transmission has occurred, and $s(i, m) = 0$ if it has not. Both α and k are included in the message sent by the BS at the start of a contention period. Suitable choices for α, and k are also matters of optimization and are later discussed. In all the time slots, each user ensures that $p(i, m+1)$ is in [0,1], by mapping negative numbers to 0, and any number larger than 1 to 1.

The whole access strategy is presented in Figure 4.1. As mentioned in the previous section, the stopping criteria in our adaptive version of frameless ALOHA is the same as the original frameless scheme, meaning that the BS stops a contention period either if the fraction of resolved users reaches a desired threshold, F_{opt}, or if the instantaneous throughput has reached to 1. F_{opt} is also a parameter of optimization which will be discussed.

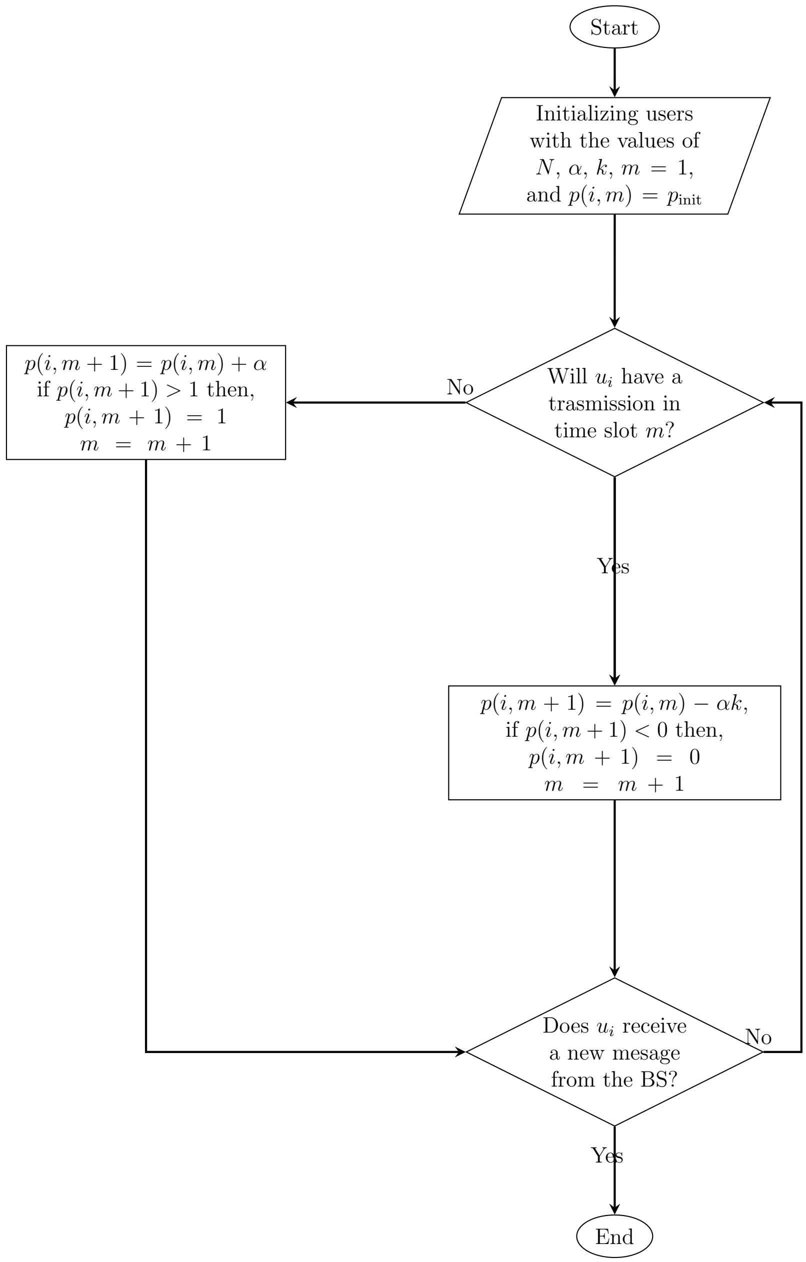

Figure 4.1: Adaptive access strategy with constant parameters.

Now, we want to define our optimization setup, consisting of our goal and constraints. We have done our optimizations to find p_{init}, α, k, and F_{R} in a way that while we have obtained a large enough required throughput T_{req}, we have minimized the average energy consumption of the network. A good index of the average energy consumption can be the average number of users transmissions per time slot. We denote the number of received messages by the BS in a given time slot, m, of the contention period, or the slot degree by $d(s_m)$. So, it can be obtained from the following equation:

$$d(s_m) = \sum_{i=1}^{N} s(i, m),\ 1 \leq m \leq M. \tag{4.5}$$

Denoting the average number of transmissions per time slot of a contention period with $[d(s_m)]_M$, we have

$$[d(s_m)]_M = \frac{\sum_{m=1}^{M} d(s_m)}{M}. \tag{4.6}$$

So, the optimization problem for our first adaptive approach can be displayed as the following:

$$\begin{aligned} \min_{\alpha, k, p_{\text{init}}, F_{\text{R}}} \quad & [d(s_m)]_M \\ \text{s.t.} \quad & T \geq T_{\text{req}}. \end{aligned} \tag{4.7}$$

The optimum outputs of this optimization are $\alpha_{\text{opt}}, k_{\text{opt}}$, $p_{\text{init}_{\text{opt}}}$, and F_{opt}. We have presented our optimization details, and results regarding this method of access in Section 4.3 of this chapter.

In the following, we will present an expression for the average probability of access of an arbitrary user in an arbitrary time slot of this scheme.

At first, we will consider that the only stopping criteria is $F_{\text{R}} \geq F_{\text{opt}}$, and we ignore that $T_{\text{I}} = 1$ can also terminate the contention period. Later, we will consider this criterion as well.

Let us first focus on transition from the first to the second time slot. As shown in Figure 4.2, when a user starts to access the channel in the first time slot, shown as the left single circle, its access probability is p_{init}, and based on whether this user will have a transmission or not its access probability in the

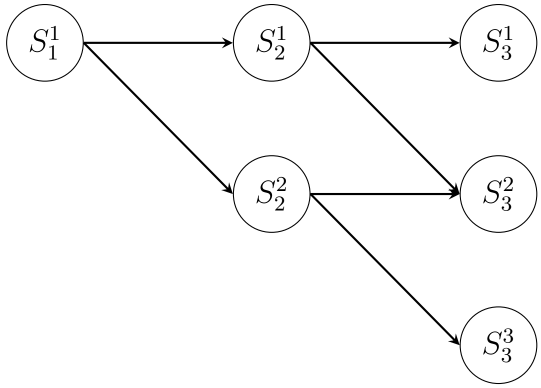

Figure 4.2: Possible scenarios in the second, and third time slots

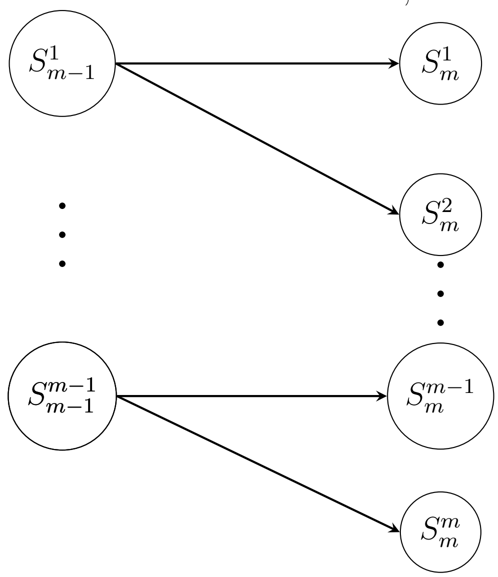

Figure 4.3: Possible scenarios in time slot m

second time slot would change to either $p_{\text{init}} - \alpha k$, or $p_{\text{init}} + \alpha$, respectively, and as the transmission happens with the probability p_{init}, and does not happen with the probability, $1 - p_{\text{init}}$ the average probability of access in the second time slot, $\bar{p}_2$, can be obtained from the following equation:

$$\bar{p}_2 = (p_{\text{init}})(p_{\text{init}} - \alpha k) + (1 - p_{\text{init}})(p_{\text{init}} + \alpha). \tag{4.8}$$

Now, let us consider time slot m. In time slot m, there are m possible states of probability coming from $m - 1$ possible probability states of the previous time slot. Figure 4.3 shows different states that a user may have in time slot m. Let S_m^n denote the n^{th} state in time slot m. In time slot m, a user may have a probability of access from the set: $\{p_{\text{init}} - (m-1)k\alpha, p_{\text{init}} - (m-2)k\alpha +$

$\alpha, \ldots, p_{\text{init}} - k\alpha + (m-2)\alpha, p_{\text{init}} + (m-1)\alpha\}$, where $p_{\text{init}} + (m-1)\alpha$ corresponds to the state S_m^1, and $p_{\text{init}} - (m-1)k\alpha$ corresponds to the S_m^m state, and all the other values in between $p_{\text{init}} - (m-1)k\alpha$, and $p_{\text{init}} + (m-1)\alpha$ correspond to the states from S_m^{m-1}, to S_m^2. The following equation indicates the probability of being in the state j, in time slot m,

$$\text{For } 1 \leq j \leq m, \quad q(m,j) = q(m-1,j)(1 - (p_{\text{init}} + (m-1-j)\alpha - (j-1)k\alpha)) + q(m-1,j-1)(p_{\text{init}} + (m-j)\alpha - (j-2)k\alpha). \tag{4.9}$$

So the average probability of access $\bar{p}_m$ in the m^{th} time slot, could be calculated from the equation below:

$$\bar{p}_m = \sum_{j=1}^{m} q(m,j)(p_{\text{init}} + (m-j)\alpha - (j-1)k\alpha). \tag{4.10}$$

Obviously in (4.10), we only account for the probabilities in the range [0,1], i.e., $0 \leq (p_{\text{init}} + (m-j)\alpha - (j-1)k\alpha) \leq 1$. In the procedure explained in Figure 4.1, when a probability reaches 0, it goes up and then continues oscillating between 0 and a small positive value, but in our calculations we ignore all the probability values that reach 0 and then oscillates. Simulations prove that the portion of probability values in this summation coming from oscillations after reaching 0, adds only a value very close to 0 to this summation. This negligibility is basically because of the fact that not only the values of those state access probabilities are so small, but also the probability of reaching to those states are also very small.

Now we consider the effect of $T_{\text{I}} = 1$ stopping criterion. If the instantaneous throughput reaches this maximum value, the contention period will stop and thus the access probability of all the users will turn to 0. In calculation of the average access probability for each time slot, we should multiply the result of (4.10) by the complement of the summation of the probability of reaching $T_{\text{I}} = 1$ in any of the $m-1$ time slots before time slot m, as they are individually exclusive. The final equation for the average probability of access in time slot

m considering both stopping criteria is indicated in the following equation, in this equation $p(T_{\mathrm{I}})_i$ refers the probability of reaching $T_{\mathrm{I}} = 1$ in time slot i.

$$\bar{p}_m = (1 - \sum_{i=1}^{m-1} p(T_{\mathrm{I}})_i)(\sum_{j=1}^{m} q(m,j)(p_{\mathrm{init}} + (m-j)\alpha - (j-1)k\alpha)). \quad (4.11)$$

In this equation, $q(m,j)$ should be substituted from the recursive equation (4.9). Both the simulation results and numerical analysis show that $p(T_{\mathrm{I}})_i$ for $i > 3$ is of a very small orders, i.e., 10^{-5} or even smaller and is thus negligible, so the approximation for $\bar{p}_m$ is as shown below:

$$\bar{p}_m = \begin{cases} p_{\mathrm{init}} & \text{m=1} \\ (1 - \sum_{i=1}^{m-1} p(T_{\mathrm{I}})_i)(\sum_{j=1}^{m} q(m,j)(p_{\mathrm{init}} + (m-j)\alpha - (j-1)k\alpha)) & \text{m=2,3} \\ (1 - \sum_{i=1}^{3} p(T_{\mathrm{I}})_i)(\sum_{j=1}^{m} q(m,j)(p_{\mathrm{init}} + (m-j)\alpha - (j-1)k\alpha)). & \text{m>3} \end{cases} \quad (4.12)$$

Using the above analysis, we can derive a sufficient condition that guarantees the total number of transmissions in our scheme to be less than that of the original frameless ALOHA. For this, we can choose $p_{\mathrm{init}} = p_{\mathrm{All}}$ of the original scheme, and force $\bar{p}_m < \bar{p}_{m-1}$. This way, the number of transmissions is reduced every time slot. Interestingly, if we let p_{init} to be an optimization parameter, we find optimal p_{init} even smaller than p_{All} of the original scheme. Hence, the total number of transmissions is further reduced compared to the original scheme.

In order to derive the desired condition, i.e., $\bar{p}_m < \bar{p}_{m-1}$, we ignore the effect of $T_{\mathrm{I}} = 1$ stopping criterion, in fact we solve the inequality for time slots $m > 3$. Although the ignorance of $T_{\mathrm{I}} = 1$ stopping criterion may not be true in practice, but it will give an approximate suitable value for k that helps to find the optimum value faster. Using the average access probability given in (4.12) for $m > 3$, and after simplifications, we reach at:

$$\sum_{j=1}^{m-1} q(m-1,j)(p_{\text{init}} + (m-1-j)\alpha - (j-1)k\alpha)$$
$$> \sum_{j=1}^{m} q(m,j)(p_{\text{init}} + (m-j)\alpha - (j-1)k\alpha). \tag{4.13}$$

Finally, we will reach to the following inequality:

$$\bar{p}_{m-1} > \frac{1}{k+1}, \tag{4.14}$$

or equivalently $k > \frac{1}{\bar{p}_{m-1}} - 1$. One problem here is that with decreasing $\bar{p}_m$, satisfying the condition on k becomes increasingly difficult, or impossible. In the next section, we suggest another access method which resolves this problem. Here, we simply force the condition at the initial step, i.e., $k > \frac{1}{p_{\text{init}}} - 1$ to reduce the optimization space. We recognize that $\bar{p}_m$ may no longer be strictly decreasing. However, simulation results show that $\bar{p}_m$ is initially decreasing and only for small $\bar{p}_m$ it may show an increasing behavior. This means, $\bar{p}_m$ is always smaller than p_{All}, hence, the total number of transmissions in our scheme, as detailed in the Simulation Result, Section 4.3, is noticeably less than that of original frameless ALOHA.

By setting the access probability at the users as discussed above, and finding the optimum values for α, k, p_{init}, and F_{R}, as α_{opt}, k_{opt}, $p_{\text{init}_{\text{opt}}}$, and F_{opt} we reduce the average access probability of the users, which in turn causes to have a lower average number of transmissions per time slot and that would bring a lower average energy consumption by the whole network.

4.2.2 Adaptive Change with Variable Parameters

One minor issue with the previous suggested method of access was that $\bar{p}_m$ was not strictly decreasing. This was caused by using a fixed k, and a decreasing $\bar{p}_m$, where the condition $\bar{p}_m > \frac{1}{k+1}$, could eventually be violated.

An idea here is to let k change adaptively, so that a decreasing $\bar{p}_m$ is always guaranteed. This, however, results in an ever increasing $k(i,m)$, where at some point, $p(i,m) - \alpha k(i,m)$ can become negative. To remedy this problem, we can let α to be also adaptive. Since the main concern is avoiding a negative probability of access, a simple choice of $\alpha(i,m)$ can be a constant which is limited whenever needed.

So, in our adaptive scheme, for user u_i at time slot m, we assume increasing and decreasing steps equal to $\alpha(i,m)$ and $\alpha(i,m)k(i,m)$ respectively, where $k(i,m)$ is a positive integer. That said, the access probability of the users is updated as follows:

$$p(i,m+1) = \begin{cases} p(i,m) - \alpha(i,m)k(i,m), & \text{if } s(i,m) = 1, \\ p(i,m) + \alpha(i,m), & \text{if } s(i,m) = 0. \end{cases} \tag{4.15}$$

The same as the previous subsection, $s(i,m)$ shows either user, u_i has had a transmission in time slot m or not. Both $\alpha(i,m)$, and $k(i,m)$ are found locally at the user. $\alpha(i,m)$ is the minimum between a value determined by the BS depending on N, i.e., α, and $\beta\frac{p(i,m)}{k(i,m)}$), where $\beta \leq 1$. The term $\beta\frac{p(i,m)}{k(i,m)}$) is to avoid negative values for $p(i,m+1)$, which is later explained in more details. So, $\alpha(i,m) = \min(\alpha, \beta\frac{p(i,m)}{k(i,m)})$, where $\beta \leq 1$. α is a parameter of optimization. Depending on N, the BS determines α and sends it to the users at the beginning of the contention period. To achieve energy efficiency, $k(i,m)$ is chosen such that u_i average access probability in the next time slot becomes less than its current probability of access. This in turn translates into less number of transmissions by the user in future time slots.

The average access probability of an arbitrary user u_i in slot $m+1$ is:

$$\begin{aligned} \bar{p}_{m+1}(i) = {} & p(i,m)[p(i,m) - \alpha(i,m)k(i,m)] \\ & + (1 - p(i,m))(p(i,m) + \alpha(i,m)). \end{aligned} \tag{4.16}$$

Now, we want to have:

$$\bar{p}_{m+1}(i) < p(i,m). \tag{4.17}$$

Using (4.16), and the desired condition in (4.17), we arrive at

$$\left(\frac{1-p(i,m)}{p(i,m)}\right) < k(i,m). \tag{4.18}$$

To have an integer $k(i,m)$, we set

$$k(i,m) = \left\lceil \frac{1-p(i,m)}{p(i,m)} \right\rceil. \tag{4.19}$$

Now we go over a discussion on α, note that in each time slot the access probability should satisfy the following condition:

$$0 \leq p(i,m+1) \leq 1. \tag{4.20}$$

For a practical network setup, reaching the upper bound is not likely to happen. However, to avoid negative probabilities, we should set $\alpha(i,m)$ such that:

$$\alpha(i,m) \leq \frac{p(i,m)}{k(i,m)}. \tag{4.21}$$

To address this, u_i sets its $\alpha(i,m)$ in time slot m, as $\alpha(i,m)=\min(\alpha, \beta\frac{p(i,m)}{k(i,m)})$, where $\beta \leq 1$. Figure 4.4 shows the procedure through which, user u_i finds its access probability $p(i,m)$, in time slot $1 \leq m \leq M$, where M is not a priori determined.

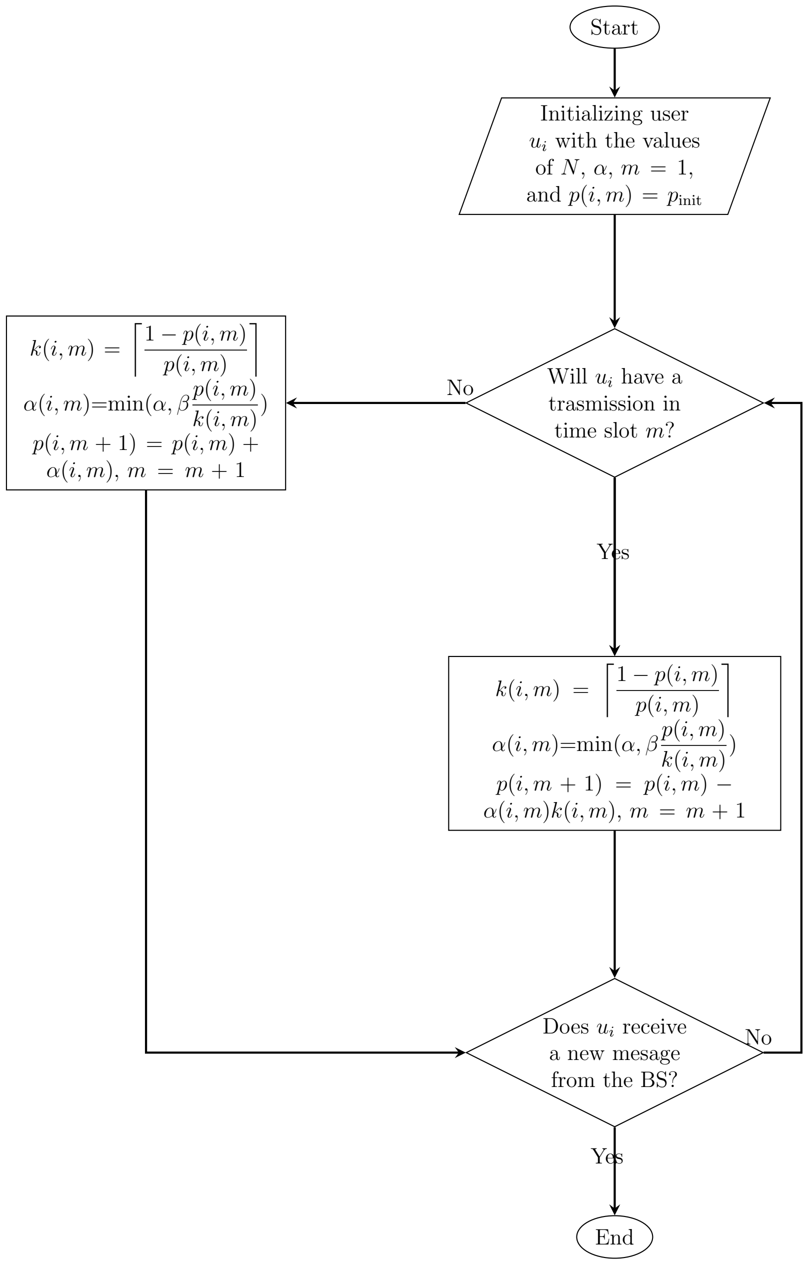

Figure 4.4: Adaptive access strategy with variable parameters.

As our goal in this proposed frameless scheme is to reduce the energy consumption, we can outline an optimization problem to find the parameters α, p_{init}, and F_{R} in a way that we minimize the average energy consumption, or the average number of transmissions per time slot $[d(s_m)]_M$, while achieving a required throughput T_{req}. This optimization problem is displayed below:

$$\begin{aligned} \min_{\alpha, p_{\text{init}}, F_{\text{R}}} \quad & [d(s_m)]_M \\ \text{s.t.} \quad & T \geq T_{\text{req}}. \end{aligned} \tag{4.22}$$

The outputs of this optimization are indexed by "opt", i.e., α_{opt}, $p_{\text{init}_{\text{opt}}}$, and F_{opt}. α_{opt}, and $p_{\text{init}_{\text{opt}}}$ will be transmitted to the users at the start of a contention period, and F_{opt} will be used as the stopping criterion for F_{R} at the BS.

Note that by setting the access probability at the users as discussed in this section, we gradually reduce the average access probability of the users. This in turn causes to have a lower average number of transmissions per time slot, and that would lead to a lower average energy consumption by the whole network. However, it is important to carefully choose α_{opt}, $p_{\text{init}_{\text{opt}}}$, and F_{opt} such that the throughput of the modified frameless ALOHA is not less than a required throughput. Assigning these parameters and finding their optimal values are discussed in Section 4.3.3 of this chapter.

4.3 Simulation Results

Before going through the results, we define some common elements among all the simulations.

Similar to slot degree $d(s_m)$, which is the number of received messages by the BS in a given time slot, m, we define user degree $d(u_i)$, as the number of replicas of the message sent by user u_i, during the contention period,

$$d(u_i) = \sum_{m=1}^{M} s(i, m) \; 1 \leq i \leq N,. \tag{4.23}$$

Now, we define the average number of transmissions per user $[d(u_i)]_N$, as

$$[d(u_i)]_N = \frac{\sum_{i=1}^{N} d(u_i)}{N}. \tag{4.24}$$

In all tables of this section, $[[d(s_m)]_M]_{\text{Runs}}$, and $[[d(u_i)]_N]_{\text{Runs}}$ are the average number of transmissions per time slot and per user that is averaged over 10000 runs. We consider $\bar{p}_m$ as the average probability of access over the users in time slot m, i.e.:

$$\bar{p}_m = \frac{\sum_{i=1}^{N} p(i,m)}{N}. \tag{4.25}$$

We define $[\bar{p}_m]_M$ as the average of $\bar{p}_m$ over all time slots in a contention period. In addition, $[[\bar{p}_m]_M]_{\text{Runs}}$ denotes the average of $[\bar{p}_m]_M$ over the 10000 runs. Also, $[F_{\text{R}}]_{\text{Runs}}$ is the fraction of resolved users averaged over the 10000 runs respectively. Finally, $\frac{[M]_{\text{Runs}}}{N}$ is the ratio of the average number of time slots in a contention period over the number of contending users.

In this section, we compare the original frameless ALOHA with our proposed adaptive access strategies as discussed in Section 4.2.

In all the schemes of this section, SIC is executed to resolve the user transmissions. The contention period terminates either when $F_{\text{R}} \geq F_{\text{opt}}$ or $T_{\text{I}}(m) = 1$, where F_{opt} is found through optimizations for each scheme. All the optimizations are performed through searching over the parameters of optimizations in each scheme. Simulations are performed by averaging over 10000 runs on each desired set of parameters in each scheme and for each $N \in \{25, 50, 100, 200\}$.

The set of values that lead to the maximum average throughput in the original frameless scheme, $[T_{\max}]_{\text{Runs}}$, are denoted as $P_{\text{All}_{\text{opt}}}$, and F_{opt} in the corresponding table. Further, the set of values that lead to $[T_{\max}]_{\text{Runs}}$ while the average number of transmissions per time slot is minimized in the adaptive access schemes, are denoted as α_{opt}, k_{opt}, $P_{\text{init}_{\text{opt}}}$, and F_{opt} in their corresponding tables. Finding the optimal value of $P_{\text{All}_{\text{opt}}}$, $P_{\text{init}_{\text{opt}}}$, F_{opt}, α_{opt}, and k_{opt} for each N in the three following schemes is done through a numerical grid search. For each combination of the set of desired values in each scheme, a simulation is run 10000 times, and the resulting $T_{\max}$, F_{R}, $[d(s_m)_M]$, $[[d(u_i)]_N]$, $[[\bar{p}_m]_M]$ and M are averaged over all the simulation runs.

4.3.1 Original Frameless Slotted ALOHA

In the original frameless slotted ALOHA, the optimization goal is to find the optimal access probability, $p_{\text{All}_{\text{opt}}}$, and stopping criterion F_{opt} for different number of users N leading to the maximum possible throughput.

N	25	50	100	200
$P_{\text{All}_{\text{opt}}}$	0.094	0.054	0.028	0.0147
F_{opt}	0.84	0.84	0.88	0.86
$[T_{\max}]_{\text{Runs}}$	0.80	0.82	0.84	0.85
$[[d(s_m)]_M]_{\text{Runs}}$	2.06	2.40	2.48	2.63
$[[\bar{p}_m]_M]_{\text{Runs}}$	0.094	0.054	0.028	0.0147
$[[d(u_i)]_N]_{\text{Runs}}$	2.32	2.68	2.68	2.77
$[F_{\text{R}}]_{\text{Runs}}$	0.72	0.76	0.77	0.78
$\frac{[M]_{\text{Runs}}}{N}$	0.99	0.99	0.96	0.94

Table 4.1: Performance of the original frameless ALOHA.

The following two subsections, include the simulation results for our proposed adaptive access strategies that lead to a lower energy consumption while maintaining the same throughput as the original ALOHA scheme.

4.3.2 Adaptive Change with Constant Parameters

In this modified frameless ALOHA, the optimization goal is to find $P_{\text{init}_{\text{opt}}}$, F_{opt}, α_{opt}, and k_{opt}[1], for each number of users, that leads to the minimum average

[1]Which correspond to the optimal values for P_{init}, F_{R}, α, and k in this scheme.

number of transmissions per time slot, while the throughput of the original frameless ALOHA is also achieved. In order to find the optimal values for p_{init}, and k, we have started our search using the inequality (4.14), i.e., by setting p_{init} greater than $\frac{1}{k+1}$, and through a grid search we have reached to the values in Table 4.2.

N	25	50	100	200
$P_{\text{init}_{\text{opt}}}$	0.082	0.049	0.024	0.014
F_{opt}	0.83	0.86	0.88	0.86
α_{opt}	0.001	0.0001	0.00008	0.000007
k_{opt}	7	15	23	46
$[T_{\max}]_{\text{Runs}}$	0.81	0.82	0.84	0.85
$[[d(s_m)]_M]_{\text{Runs}}$	1.86	2.17	2.23	2.54
$[[\bar{p}_m]_M]_{\text{Runs}}$	0.085	0.049	0.025	0.014
$[[d(u_i)]_N]_{\text{Runs}}$	2.03	2.38	2.36	2.65
$[F_{\text{R}}]_{\text{Runs}}$	0.68	0.73	0.72	0.77
$\frac{[M]_{\text{Runs}}}{N}$	0.93	0.96	0.91	0.93

Table 4.2: Performance of adaptive frameless ALOHA with constant parameters (k,α,P_{init}).

In order to compare our proposed access strategies with the original access strategy, we use $[[d(s_m)]_M]_{\text{Runs}}$ as the index of energy consumption. Comparing the number of transmissions per time slot in this access strategy with the original frameless ALOHA, we come to Table 4.3 below. As it can be observed, our proposed frameless ALOHA significantly decreases the number of transmission for small to medium sized networks.

N	25	50	100	200
Energy saving	9.7%	9.58%	10.08%	3.42%

Table 4.3: Reduction in the average number of transmissions per time slot when adaptive frameless ALOHA with constant parameters (k,α,P_{init}) is the random access scheme.

4.3.3 Adaptive Change with Variable Parameters

In this modified frameless access technique, the optimization goal is to find $p_{\text{init}_{\text{opt}}}$, F_{opt}, and α_{opt}[2], for each number of users with exactly the same optimization objective over the throughput and average number of transmissions per time slot, as mentioned in the previous access method. Comparing the number of transmissions per time slot in this method of access and the original one, we come to Table 4.5.

N	25	50	100	200
$P_{\text{init}_{\text{opt}}}$	0.081	0.044	0.025	0.014
F_{opt}	0.75	0.92	0.89	0.85
α_{opt}	0.0027	0.0008	0.00011	0.000002
$[T_{\text{max}}]_{\text{Runs}}$	0.79	0.82	0.84	0.85
$[[d(s_m)]_M]_{\text{Runs}}$	1.72	1.89	2.18	2.5
$[[\bar{p}_m]_M]_{\text{Runs}}$	0.079	0.043	0.025	0.014
$[[d(u_i)]_N]_{\text{Runs}}$	1.87	2.16	2.36	2.59
$[F_{\text{R}}]_{\text{Runs}}$	0.67	0.75	0.75	0.76
$\frac{[M]_{\text{Runs}}}{N}$	0.95	0.99	0.95	0.92

Table 4.4: Performance of adaptive frameless ALOHA with variable parameters ($k(i,m)$, $\alpha(i,m)$,P_{init}), for $\beta = 0.95$.

N	25	50	100	200
Energy saving	16.5%	21.25%	12.09%	4.94%

Table 4.5: Reduction in the average number of transmissions per time slot when adaptive frameless ALOHA with variable parameters ($k(i,m)$,$\alpha(i,m)$,P_{init}) is the random access scheme.

As it can be observed, our proposed frameless ALOHA significantly decreases the number of transmission for small to medium sized networks.

[2]Which correspond to the optimal values for P_{init}, F_{R}, and α in this scheme.

4.4 Comparison

Comparing our proposed adaptive schemes with the original frameless slotted ALOHA in [20], we conclude that by adaptively changing the probability of access at the users, we have been able to improve the energy efficiency while preserving the same throughput. Results show that our proposed $k(i, m)$, $\alpha(i, m)$, P_{init}, and k, α, P_{init} protocols, are able to reduce the energy consumption from 5% to an outstanding value of 21%, and from 4% to 10%, respectively depending on the number of users contending in the network. In these protocols, each user uses its local immediate information of its current probability of access, and also weather or not it had a transmission in the current time slot to change its access probability for the next slot. Therefore, by adding no memory, extra handshaking, or central monitoring we have decreased energy consumption, while maintaining the same throughput as the state-of-the-art.

Chapter 5

Conclusion

In this chapter, we conclude the thesis. In the first two chapters we discussed the motivations and the background needed for this work. Our first contribution was in Chapter 3, where we considered a network with N users in k different classes, who want to random access a shared communication channel. We obtained the achievable throughput region, and based on an optimized distribution for irregular repetition of a network with N users that transmit their messages in N time slots, we have obtained distributions to be assigned to different classes of the users. These distributions lead to the largest possible throughput region. This throughput region is shown for $N = 100$, and a network of two classes with $N_1 = N_2 = \frac{N}{2}$ in Figure 5.1. If the BS is provided with this throughput boundary, all the points inside the throughput region are achievable by easily deriving their corresponding sets of distributions for different classes. One can argue that, as far as there is no better distribution for 1 class of N users transmitting in N time slots, there will be no better throughput region than our provided one. This is because if there was a better throughput region, then the overall throughput of the network for the N users that have the overall distribution, would have been higher than the best possible(a contradiction).

In Chapter 4 of this thesis, we proposed adaptive frameless slotted ALOHA

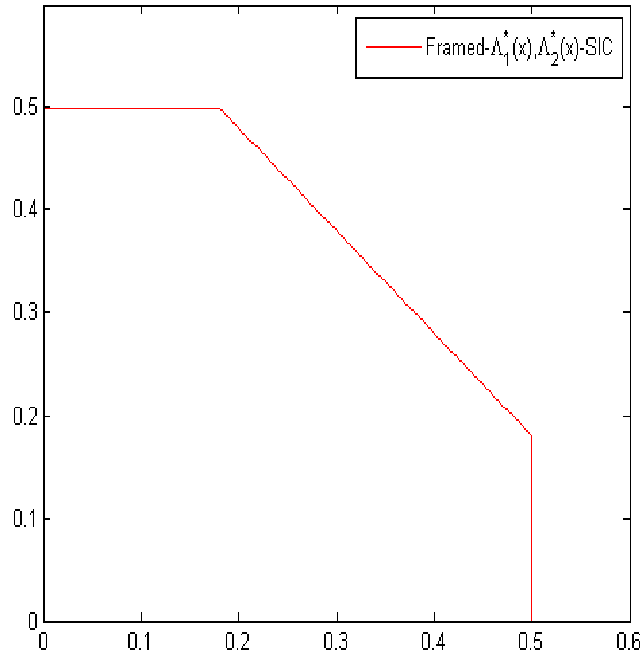

Figure 5.1: The best throughput region for a network with two classes of users, $N = 100$ time slots in a frame, and $N_1 = N_2 = \frac{N}{2}$.

schemes that provide energy efficiency in comparison to the original frameless slotted ALOHA in [20]. By adaptively changing the probability of access at the users, we are able to improve the energy efficiency while maintaining the same throughput. In the following table, we have summarized the amount of energy saving versus the number of users in a network, provided by our two adaptive frameless slotted ALOHA methods.

N	25	50	100	200
k , α, P_{init} Method	9.7%	9.58%	10.08%	3.42%
$k(i,m)$, $\alpha(i,m)$, P_{init} Method	16.5%	21.25%	12.09%	4.94%

Table 5.1: Reduction in the average number of transmissions per time slot, that translates to the amount of energy saving, when each of our two proposed methods are applied.

5.1 Future Work

One possible extension regarding our works in Chapter 4 is to find the Markov Chain steady state probabilities that could be considered for each of our proposed adaptive frameless slotted ALOHA approaches, and to find an exact formula for the average number of transmissions per time slot, as an indication of the average energy consumption.

As another work, we can develop the original frameless ALOHA scheme in a way that it can be applied to networks with users of different classes of priority. We can consider a network with N users in k classes $\{C_1, ..., C_k\}$ having their transmissions via frameless slotted ALOHA random access. Users of an arbitrary class C_n are considered to have access probability p_n. Further, at the BS instead of using a single stopping criterion for the whole resolved users, we can consider different stopping criteria for each of the classes. For example considering the fraction of resolved users, there should be different thresholds for each of the classes as $\{F_1, ..., F_k\}$ which will lead to a specific set of throughputs $\{T_1, ..., T_k\}$. Assigning different possible values for the two set, $\{p_1, ..., p_k\}$, and $\{F_1, ..., F_k\}$ leads to a throughput region. This way, we may achieve an even larger throughput region than our proposed framed slotted ALOHA with irregular repetition, but this is at the expense of a non-fixed frame, and performing optimizations instead of assigning easy to derive distributions.

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