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Random Multiple Packet Access with Channel Sensing for an Energy Limited Cognitive Radio System

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Chania, March 2016

Abstract

Cognitive radio has emerged as an efficient approach to implement reuse of the licensed spectrums. How to appropriately deploy and construct the secondary network plays an important role. Several cognitive medium access control (MAC) protocols have been proposed for the secondary users (non-licensed users) to access the underutilized spectrum. In this thesis we consider a secondary user with energy harvesting capability. We design access schemes for the secondary user which incorporate random spectrum sensing and random access. The sensing and access probabilities of the secondary user, are dynamically computed such that the secondary user throughput is achieved is high, under the constraints that the primary queue is stable and that the primary queueing delay is kept low, in order to guarantee a quality of service (QoS) for the primary user.

Acknowledgements

First of all, I would like to thank my family for their support and encouragement in all these years.

I, also, would like to thank my friends in Chania, *Christos, Dimitris, Konstantinos, Dimosthenis, Giorgos, Manos, Thodoris, Stathis, Vaggelis and Vassilis* for their support and for the great time that we had as students.

Finally, I wish to thank my supervisor, Professor *Michael Paterakis*, for his patience, support and guidance he gave me.

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Chapter 1

Introduction

The exponential growth in wireless services has resulted in a crowded spectrum. The current state of spectrum allocation indicates that almost all usable radio frequencies have already been occupied. This makes one pessimistic about the feasibility of integrating emerging wireless services. Although, extensive measurements have shown that, at any given time and location, a large portion of licensed spectrum lies unused [1]. Even when a channel is actively used, the bursty arrivals of many applications results in inevitable spectrum underutilization. In Figure 1.1 we can see the average spectrum occupancy in Chicago and New York.

This spectrum's underutilization , has lead to the Opportunistic Spectrum Access (OSA). OSA has received increasing attention due to its potential for improving spectrum efficiency. The basic idea of OSA is to allow Secondary Users (SU) to search for and exploit local and instantaneous spectrum opportunities under the constraint that the Primary User (PU) has a certain Quality of Service (QoS). The physical platform of OSA and other dynamic spectrum access strategies is cognitive radio. A cognitive radio is defined as an intelligent wireless communication system that is fully aware of its environment and uses methodologies of learning and reasoning in order to dynamically adapt its transmission parameters (e.g., operating spectrum, modulation and transmission power) to access portions of spectrum by exploiting the existence of spectrum holes left unused by a PU [2].

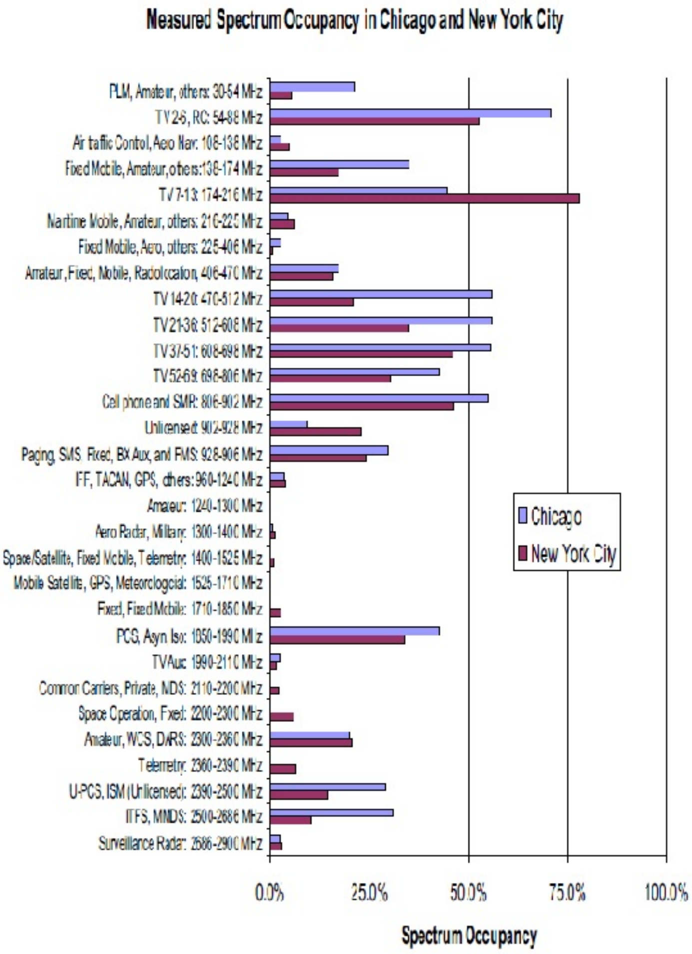


Figure 1.1: Average spectrum occupancy by band in Chicago and New York

In a typical cognitive radio system, the SU senses the channel and decides whether to access or not the channel based on the sensing outcome. This approach is problematic because depending on spectrum sensing only does not inform the SU about its impact on the primary receiver. This issue has lead to an interest in utilizing the feedback from the primary receiver to the primary transmitter. The authors of [3] proposed a feedback based random access scheme where the SU does not sense at all the channel and accesses it randomly with some probability that depends on the feedback that the SU overhears from the primary receiver.

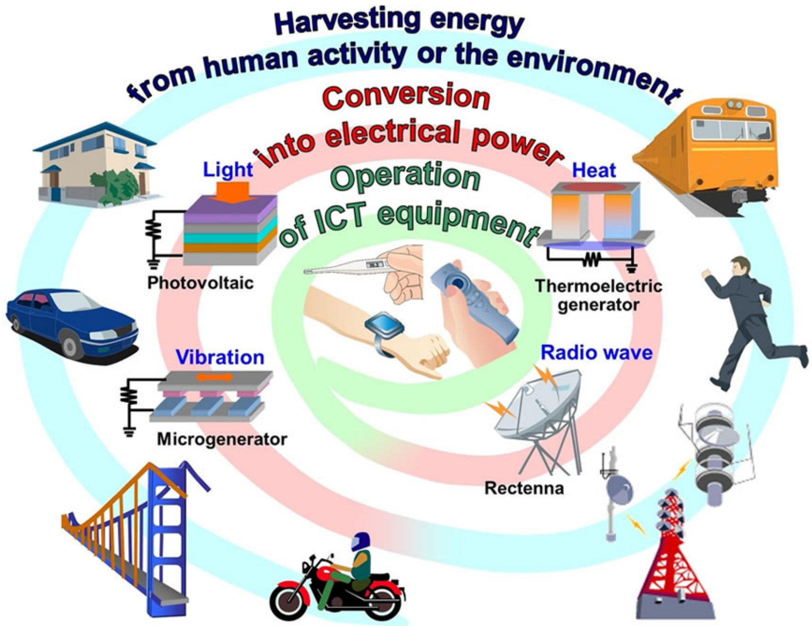


Figure 1.2: Types of energy sources

In many situations the SU is a battery-powered devise where spectrum sensing and access consume energy. Because of this energy limitation, the SU must optimize its sensing and access decisions in order not to waste energy. An emerging technology for battery-powered devices is energy harvesting which gives the ability to the transmitter to gather energy from its environment (see figure 1.2). In [4] we can see an overview of the different energy harvesting technologies.

1.1 Thesis Contribution

We investigate a system that consists of one PU and one SU. The SU is equipped with a rechargeable battery and it has energy harvesting capabilities. We propose probabilistic random access and sensing schemes, where the probabilities depend on an estimation we propose of the primary user arrival rate. First, the SU decides whether it will be active or not, in the current time slot, in order to conserve energy. Assuming it decides to be active, then it decides to sense the channel and to access it, if it is sensed to be free, or to directly access the channel attempting to transmit over the entire time slot. We assume that the SU has always packets and available energy, for transmission, in order to find the maximum interference it can cause to the PU and the maximum throughput the SU can achieve with our scheme. Finally, we compare our scheme with two other similar schemes published in the literature (see chapter 4).

1.2 Thesis Overview

The rest of the thesis is organized as follows. In chapter 2 we provide some background information about cognitive radios and their applications, energy harvesting sources and techniques as well as useful properties and types of Poisson processes. In chapter 3 we introduce and propose an access scheme for the SU and we discuss some simulation results. In chapter 4 we evaluate our scheme by comparing it with similar previously published access schemes. Finally, in chapter 5 we conclude the thesis.

Chapter 2

Background

2.1 Cognitive Radios

The rapid growth in wireless services has lead to an crowded spectrum and there is a common belief that we are running out of usable radio frequencies. Despite the fact that almost all usable radio frequencies have already been assigned to licensed users, extensive measurements have shown that, at any given time and location, a large portion of the licensed spectrum remains unused.

Cognitive Radio technology has been developed in order to utilize the unused spectrum by giving the ability to unlicensed users to access it . According to Mitola's work in [5], cognitive radio is a goal-driven framework in which the radio autonomously observes the radio environment, assesses alternatives, generates plans, supervises multimedia services and learns from its mistakes (refer the cognition cycle in Fig. 2.1).

2.1.1 Definitions of Cognitive Radio

Cognitive radio has drawn great attention due to its potential for solving current spectrum shortage problems and enhancing radio communications performance. This resulted in many academic institutions and industries generating various definitions for cognitive radios. The most important of those definitions are:

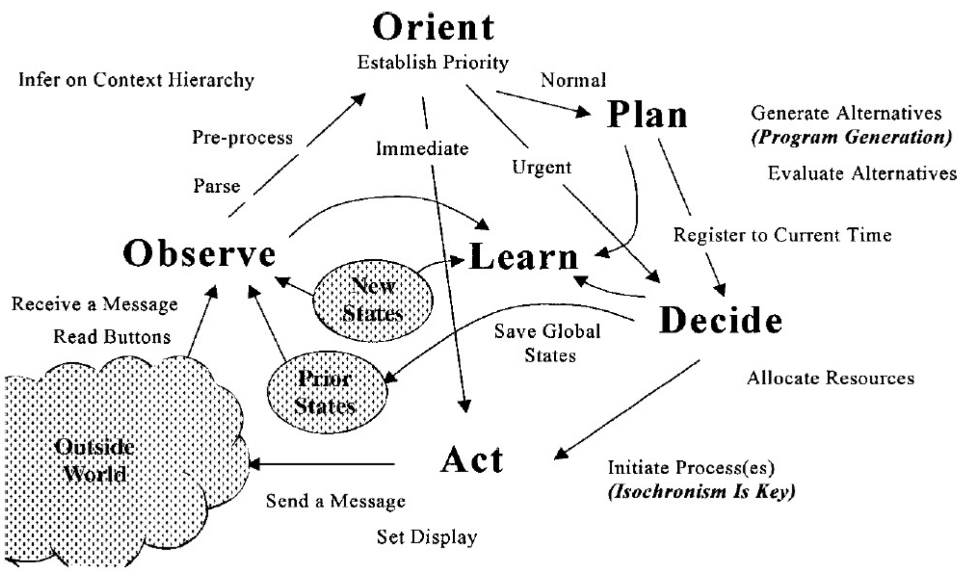


Figure 2.1: The cognition cycle

By Joseph Mitola [5]

"Cognitive radio signifies a radio that employs model-based reasoning to achieve a specified level of competence in radio-related domains"

By Simon Haykin [6]

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- *highly reliable communications whenever and wherever needed;*
- *efficient utilization of the radio spectrum."*

By James O'Daniell Neel [7]

"A cognitive radio is a radio whose control processes permit the radio to leverage situational knowledge and intelligent processing to autonomously adapt towards some goal."

By SDR forum [8]

A Cognitive Radio is:

a) *"Radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information. The environmental information may or may not include location information related to communication systems*

b) *Radio (as defined in a.) that utilizes Software Defined Radio, Adaptive Radio, and other technologies to automatically adjust its behavior or operations to achieve desired objectives."*

2.1.2 Capabilities of Cognitive Radio

There are many other definitions for cognitive radios in addition to the definitions presented in the previous section, but we can see that there are some common radio capabilities in these definitions. These are:

- *Observation* - the radio is capable of collecting information about its environment,
- *Adaptability* - the radio is capable of changing its operating parameters (e.g. transmit power, carrier frequency and modulation strategy),
- *Intelligence* - the radio is capable of understanding its environment and how its actions influence its own performance.

2.1.3 The Cognition Cycle

Joseph Mitola in [5] describes how a cognitive radio can adapt its operation parameters through a cognitive cycle. This six stage cognition cycle is:

Observe: know the information of its environment though sensing and signaling mechanisms

Orient: evaluate this information in order to determine its importance

Plan: Based on this evaluation, the radio determines its options or alternatives for resource optimization

Decide: an alternative is chosen that evaluates better than the others

Act: the radio implements the decisions taken before

Learn: the radio uses its observations and decisions to improve its own operation, creating new alternatives.

2.1.4 Applications of Cognitive Radio

Cognitive radio has many applications in our life and those applications show us the importance of cognitive radio. Some of these applications, are presented in [9] and the references therein. They are:

Applications in Personal Level

- **Office Environment:** in an office environment, cognitive radio can prioritize a radio network connection according to pre-set priority status. For example, e conference can receive the highest priority in network connection and available spectrum occupancy. The priorities can be set at times of network initialization and can be updated on a regular basis and they can vary in time, location, space or according to the employee rank.
- **Roaming Across Borders:** cognitive radio can allow the user to roam across borders with variable policy and can negotiate with several providers to establish a connection with the lowest cost.
- **Man-Machine Interface:** one of the first cognitive concept proposed by Mitola is the autonomous interaction between a communication devise and its user. Some of the cognitive radio applications that can directly involve the user are:
  - *User Authentication:* cognitive radio can be aware of each user's unique identification.
  - *Noise Cancellation:* cognitive radio can detect the environment noise around the receiver and apply noise cancellation techniques dynamically to adapt, adjust and maintain desired signal quality.

- *User Habits:* during initialization phase, cognitive radio can learn about its user's periodic habits and can utilize this knowledge to make decisions in radio communications.

Applications in Public Protection, Safety, Security and Disaster Relief

The applications of cognitive radio in public safety and disaster situations can bring significant changes. Cognitive radio enables creation and maintenance of communication over diverse networks and spectrums. In a disaster situation, the private wireless networks can be overcrowded due to numerous emergency connections. Under such situation, cognitive radio can utilize available licensed and unlicensed spectrum holes and heterogeneous network components to create and maintain temporary emergency connection. As an example, cognitive radio can establish a communication link over GSM bands using WLAN access points.

- **Emergency Management or Disaster Recovery:** the communications is of vital importance to carry out emergency responses and disaster relief operations. In the recent years, it is proved from experience that the communication systems fail to meet peoples needs when they are needed the most. Cognitive radio can resolve these problems in disaster situations. For example, various nodes can work as a relay to establish communication when there is a power outage or a lost of central control.
- **Fire Services:** fire fighters work under severe conditions of extremely high temperature and high humidity. Wireless equipments are required to function under such conditions that force communication over atypical channel characteristics. For example, in case of wild land fires, wireless equipments need to cover a wide range of landscapes and autonomously reconfigure with respect to the available communication link.
- **Search and Rescue:** since the wireless coverage is limited in remote areas, it may be impossible for the distressed person to inform the rescuer using a wireless devise. The cognitive radio of the distressed and the rescuer can establish communication without any central control. The GPS capability of cognitive radio can lead to the detection of the position of the distressed

person. At the same time, if a special channel over available spectrum is used for short range signaling, this channel can work like a beacon for the distressed person.

- **Crime Prevention:** the crime prevention sectors of the government can benefit from utilizing the cognitive radio. The operations of these sectors demand portable coverage with transparent and high-speed access to public safety files for criminal identification and investigation. Also, it is important to transfer the data securely so that unauthorized users do not get or corrupt the transferred information.
- **Traffic Control:** traffic is a big problem especially during the rush hours. The local traffic control can transmit the congested traffic location, the predicted traffic delay and an alternative route to the mobile users. Also cognitive intelligence can be applied on traffic signals to determine how long the red or green signal will remain on depending on the traffic volume in each direction.
- **Medical Applications:** patients can be provided with a personal cognitive ID tag. A central control within the same hospital unit can utilize, store, and update each patient information and keep track of their changes. The cognitive tag can record the vital signs of the patient and intelligently inform the respective authority if an abnormality is detected. Modern advances in the medical fields provide emergency services the ability to serve advanced level of medical assistance. The mobile medical personnel wireless systems can help transfer information of the patient to the controlled environment. This information transmission requires sufficient bandwidth and may include video and sound that are gathered by the medical equipments on the mobile unit. It is of vital importance to transmit the information in a fast and reliable way so that specific medical preparations can be made at the controlled environment before the patient reaches there.
- **Weather Forecast:** Sensors and sensor networks have been employed in detecting weather parameters such as temperature, wind speed, air pressure, and humidity for over a long time. If these sensors are equipped with cognitive ability, they can communicate with each other without any user intervention. This way the sensors out in the field can detect, collect and share information

among themselves for optimum performance. When the required amount of data is collected, the data can be passed to the central control by the sensor closest to the station for optimum power and network usage and minimized delay.

Applications in Military

Wireless communication has been the critical factor in military combat scenarios. The ability to communicate and destroy the communication of the enemy is very important for modern armies. There has been a strong need to deploy jammers properly in the battle fields so that the communication of the enemy is disrupted. On the other hand, there is also strong need to protect our own communication against the enemy jammers. This requires identification and position of jamming signal and shaping our own communication signal so that the jamming signal's effect will be minimal. For example, employing jamming interference cancellation, deploying adaptive frequency hoping, etc. require various information as well as statistics about about the interfering signal.
Cognitive radio can coordinate a series of devices to stimulate a physical action to remove jamming and adjust communication waveforms to avoid jams that are intentionally applied in the military markets. The cognitive radio can identify the signal type (for example, multi-carrier or single carrier signal, frequency hoping or not, Code Division Multiple Access type or not, wideband or narrowband,etc.), signal modulation (such as Quadrature Amplitude Modulation, OFDM, Adaptive versus fixed modulation, etc.), occupied bandwidth, carrier frequency, number of signals over the selected band, signal statistics (such as temporal, spatial, and frequency), and estimate the geolocation of the radio source (enemy jammers or signals) from the captured enemy signal.

2.2 Energy Harvesting

In many situations in wireless networks a user is powered by a battery, meaning that such users have the limitation of finite battery capacity and they can operate as long as the battery lasts. Battery-powered users may use larger batteries for longer lifetimes, but

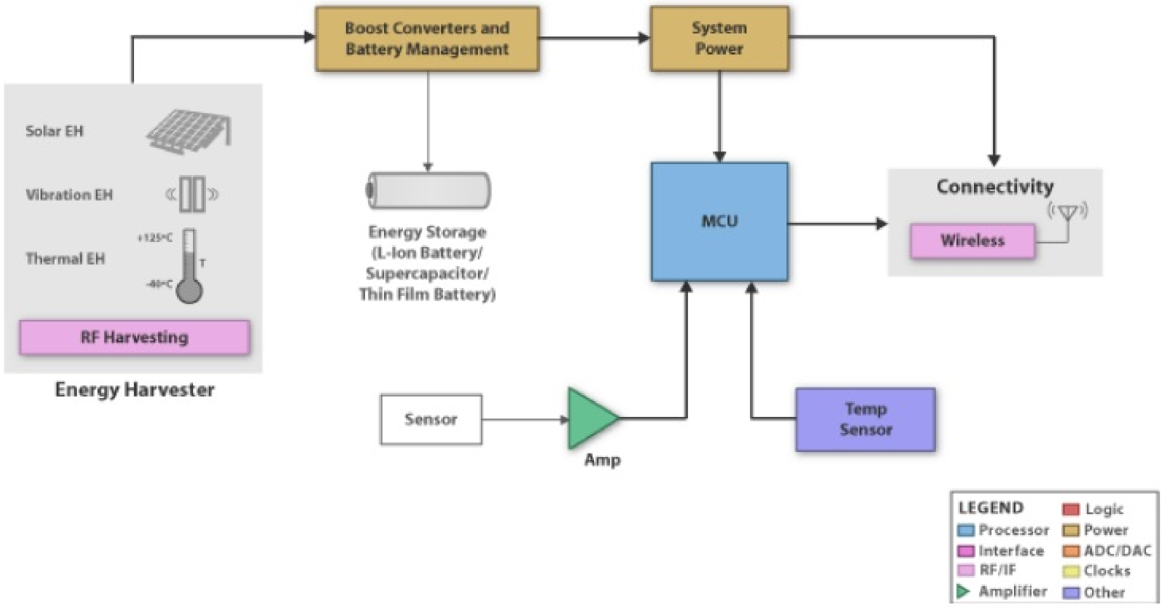


Figure 2.2: A blog diagram of an energy harvesting application from *Texas Instruments*

this means larger size, weight and cost. They may also use low-power hardware like a low-power processor and radio, resulting in larger battery lifetime but less computation ability and lower transmission range.

The solution that addresses this tradeoff between performance parameters and battery's lifetime is energy harvesting. Energy harvesting refers to harvesting energy from the environment or other energy sources and converting it to electrical energy. According to the survey in [4], a typical energy harvesting system has three components:

- *Energy Source:* refers to the ambient source of energy to be harvest,
- *Harvesting Architecture:* consists of mechanisms to harvest and convert the input ambient energy to electrical energy and
- *Load:* refers to the activity that consumes the electrical energy.

2.2.1 Sources of Harvestable Energy

A vital component of any energy harvesting system is the energy source. Energy sources have the following characteristics:

- *Controllability:* a controllable energy source can provide harvestable energy whenever is required. With a non-controllable energy source, energy must be harvested whenever is available.

- *Predictability:* refers to a non-controllable energy source. When it is predictable, we can predict the next recharge cycle in order to utilize properly the available remaining electrical energy.

Furthermore, energy sources can be classified into the following two categories:

- *Ambient Energy Sources:* are the sources of energy from the environment as solar energy, wind energy e.t.c.

- *Human Power:* passive human power sources that are not user controllable (blood pressure, body heat, breath) and active human power sources that are under user control and the user performs a specific action to generate the energy for harvesting (finger motion, walking, paddling).

In Fig 2.3 we can see some energy sources and their characteristics.

2.2.1.1 Energy Harvesting Architectures

Energy harvesting can be divided into two architectures:

- *Harvest-Use:* the harvesting system directly powers the user. The power output of the harvesting system has to be continuously above the minimum power that the user needs. If sufficient energy is not available, the user can not operate. A Harvest-Use system can be built to use mechanical energy sources like pushing keys/buttons, walking, pedaling, etc. For example, the push of a key/button can be used to deform a piezo-electric material, thereby generating electrical energy to send a short wireless message.

Energy Source	Characteristics	Amount of Energy Available	Harvesting Technology	Conversion Efficiency	Amount of Energy Harvested
Solar[25], [26], [27], [28]	Ambient, Uncontrollable, Predictable	$100mW/cm^2$	Solar Cells	15%	$15mW/cm^2$
Wind[28]	Ambient, Uncontrollable, Predictable	-	Anemometer	-	1200mWh/day
Finger motion[22], [24]	Active human power, Fully controllable	19mW	Piezoelectric	11%	2.1mW
Footfalls[22], [24]	Active human power, Fully controllable	67W	Piezoelectric	7.5%	5W
Vibrations in indoor environments[29]	Ambient, Uncontrollable, Unpredictable	-	Electromagnetic Induction	-	$0.2mW/cm^2$
Exhalation[24]	Passive human power, Uncontrollable, Unpredictable	1W	Breath masks	40%	0.4W
Breathing[24]	Passive human power, Uncontrollable, Unpredictable	0.83W	Ratchet-flywheel	50%	0.42W
Blood Pressure[24]	Passive human power, Uncontrollable, Unpredictable	0.93W	Micro-generator	40%	0.37W

Figure 2.3: Listing and characterization of energy sources

- *Harvest-Store-Use:* this architecture consists of a storage component that stores harvested energy and also powers the user. Energy storage is useful when the harvested energy available is more than its current usage. Alternatively, energy can also be stored until enough has been collected for system operation and to be used later when either harvesting opportunity does not exist or energy usage of the user has to be increased to improve capability and performance parameters. As an example, a Harvest-Store-Use system can use uncontrolled but predictable energy sources like solar energy, during the daytime, energy is used for work and also stored for later use. During night, the stored energy is used to power the user.

2.3 Poisson Process

A number of different types of traffic as Ethernet,web, video and disc traffic are bursty. Many methods have been proposed to simulate this kind of traffic but the Poisson arrival model is the most common, simple and widely used stochastic process for modeling bursty traffic.

A Poisson process is a stochastic process which counts the number of events and the time that these events occur in a given time interval. The time between each pair of consecutive events has an exponential distribution with parameter λ and each of these inter-arrival times is independent of the other inter-arrival times. The process is named after the French mathematician Simeon Denis Poisson [10].

2.3.1 Definition

The Poisson process can be defined in three different but equivalent ways [11]:

- Poisson process is a pure birth process for which in any infinitesimal time interval dt there may occur only one arrival. This happens with the probability λdt, independently of the arrivals outside that interval.

- The number of arrivals $N(t)$ in a finite interval of length t obeys the Poison distribution with parameter λt:

  $$P\{N(t) = n\} = \frac{(\lambda t)^n}{n!} e^{-\lambda t}$$

  Furthermore, the number of arrivals $N(t_1, t_2)$ and $N(t_3, t_4)$ in non-overlapping intervals $(t_1 \leq t_2 \leq t_3 \leq t_4)$ are independent random variables.

- The interarrival times are independent random variables and obey the exponential distribution with parameter λ:

  $$P\{\text{any interarrival interval} > t\} = e^{-\lambda t}$$

2.3.2 Types of the Poisson Process

- **Homogeneous**
  The homogeneous Poisson process is one of the most well-known *arrival processes*. This process is characterized by a rate parameter λ, also known as *intensity*, such that the number of events in a time interval $(t, t + \tau]$ follows a Poisson distribution with associated parameter $\lambda\tau$. This relation is given as:

  $$P\{N(t + \tau) - N(t) = k\} = \frac{e^{-\lambda\tau}(\lambda\tau)^k}{k!}, \qquad k = 0, 1, 2, \ldots$$

where $N(t+\tau) - N(t)$ is the number of arrivals in the time interval $(t, t+\tau]$.
A homogeneous Poisson process is characterized by its rate parameter λ, which is the expected number of "events" or "arrivals" that occur per unit time.

- **Non-homogeneous**
  In general, the rate parameter may change over time. Such a process is called *non-homogeneous* or *inhomogeneous* Poisson process. In this case, the generalized rate function is given as $\lambda(t)$. The expected number of events between time a and time b is:
  $$\lambda_{a,b} = \int_a^b \lambda(t)dt$$
  The number of of arrivals in the time interval $(a, b]$, given as $N(b) - N(a)$, follows a Poisson distribution with associated parameter $\lambda_{a,b}$:
  $$P\{N(b) - N(a) = k\} = \frac{e^{-\lambda_{a,b}}\lambda_{a,b}^k}{k!}, \qquad k = 0, 1, 2, \ldots$$
  A rate function $\lambda(t)$ in a non-homogeneous Poisson process can be either a deterministic function of time or an independent stochastic process. The homogeneous Poisson process may be viewed as a special case when $\lambda(t) = \lambda$, a constant rate.

- **Spatial**
  An important variation on the Poisson process is the spatial Poisson process. In the case of a one-dimension space the theory differs from that of a time-based Poisson process only in the interpretation of the index variable. For higher dimension spaces, where the index variable is in some vector space V (e.g. $\mathbb{R}^2$ or $\mathbb{R}^3$), a spatial Poisson process can be defined by the requirement that the random variables defined as the counts of the number of "events" inside each of a number of non-overlapping finite sub-regions of V should each have a Poisson distribution and should be independent of each other.

- **Space-time**
  A further variation on the Poisson process, the space-time Poisson process, allows for separately distinguished space and time variables. Even though this can theoretically be treated as a pure spatial process by treating "time" as just another component of a vector space, it is convenient in most applications to treat space and

time separately, both for modeling purposes in practical applications and because of the types of properties of such processes that it is interesting to study.
In comparison to a time-based inhomogeneous Poisson process, the extension to a space-time Poisson process can introduce a spatial dependence into the rate function, such that it is defined as $\lambda(x, t)$, where $x \in V$ for some vector space V (e.g. $\mathbb{R}^2$ or $\mathbb{R}^3$). However a space-time Poisson process may have a rate function that is constant with respect to either or both of x and t. For any set $S \subset V$ (e.g. a spatial region) with finite measure $\mu(S)$, the number of events occurring inside this region can be modeled as a Poisson process with associated rate function $\lambda_S(t)$ such that:

$$\lambda_S(t) = \int_S \lambda(x, t) d\mu(x).$$

2.3.3 Useful Properties of the Homogeneous Poisson Process

The Poisson process has several interesting and useful properties [11]:

- *Conditioning on the number of arrivals:* given that in an interval of length t the number of arrivals is n, these n arrivals are independently and uniformly distributed over the interval.

- *Superposition:* the superposition of two independent Poisson processes with parameters λ_1 and λ_2 is a Poisson process with parameter $\lambda = \lambda_1 + \lambda_2$.

- *Random selection:* if a random selection is made from a Poisson process with parameter λ such that each arrival is selected with probability p, independently of the others, the resulting process is a Poisson process with parameter $p\lambda$.

- *Random split:* if a Poisson process with parameter λ is randomly split into two processes with probabilities p_1 and p_2, where $p_1+p_2 = 1$, then the resulting processes are independent Poisson processes with parameters $p_1\lambda$ and $p_2\lambda$.

- *Poisson Arrivals See Time Averages (PASTA):* when customers with Poisson arrivals have independent interarrival and service times, then they observe the system occupancy as if they came into the system at a random instant of time.

Chapter 3

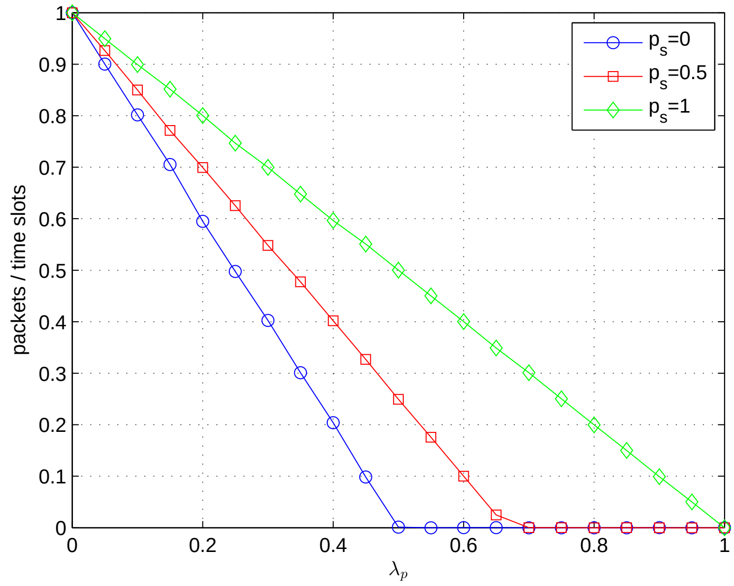
Our Approach

3.1 A Typical Access Scheme

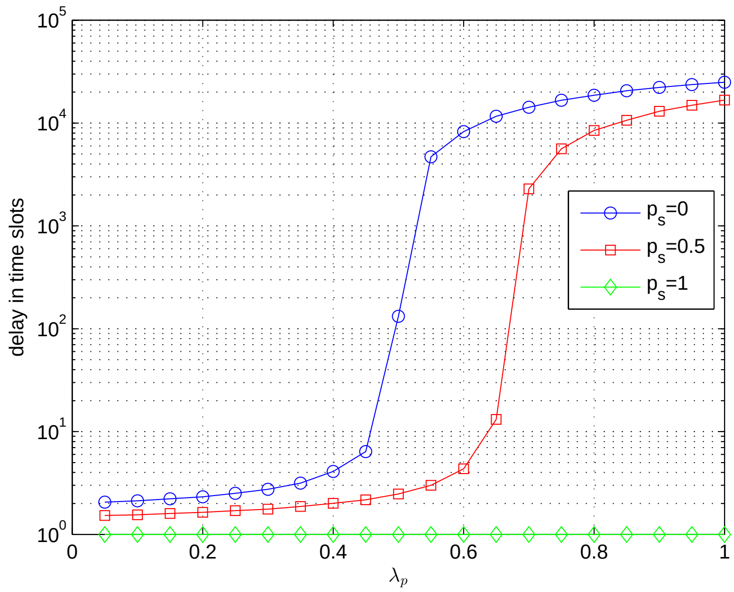
We started our work with a simple, feedback based, random access scheme which consists of one PU and one SU. The channel is slotted in time and a slot duration equals the packet transmission time. The PU and SU have infinite buffer queues Q_p and Q_s to store fixed-length packets. The SU has also an infinite buffer queue Q_e to store harvested energy from the environment. The arrivals at Q_p, Q_s and Q_e are assumed independent and identically distributed Bernoulli random variables with means λ_p, λ_s and λ_e respectively. To simplify our analysis and presentation, we assume that a packet will be transmitted correctly if only one user is transmitting and the probability that the SU makes an error in the sensing of the PU activity is negligible.

In this scheme PU accesses the channel whenever it has a packet to send and the SU monitors the PU feedback and makes use of the PUs automatic repeat request (after a collision, the PU will access the channel with probability one) in order to decide how to act. SU may overhear an acknowledgment (ACK) if the PU sends correctly a packet, a negative acknowledgment (NACK) if the PU fails to send a packet, or nothing if the PU remains idle (does not have a packet to send). According to the feedback that the SU will overhear, he will act as follows:

- If a NACK is overheard, the SU knows that the PU will retransmit the lost packet during the next time slot. Therefore, the SU will remain idle in the next time slot



(a)



(b)

Figure 3.1: Service rate for SU (a) and average delays of PU's packets (b) for different values of p_s.

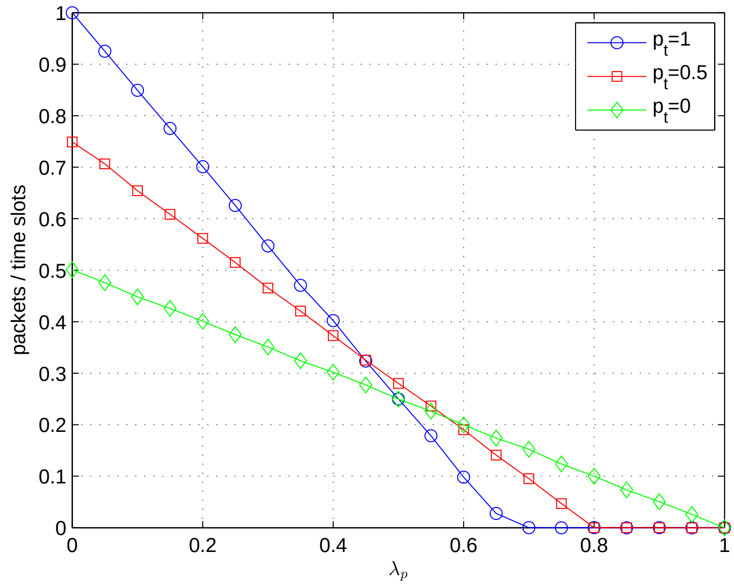
in order to avoid a sure collision .

- If an ACK is overheard or no primary feedback is overheard (idle PU), provided that the SU has energy and data to send it decides whether to sense the channel or not with probability p_s.
  - If the SU decides to sense the channel and the channel is sensed to be free, then the SU accesses the channel, otherwise it remains idle.
  - If the SU decides not to sense the channel, then it accesses directly the channel.

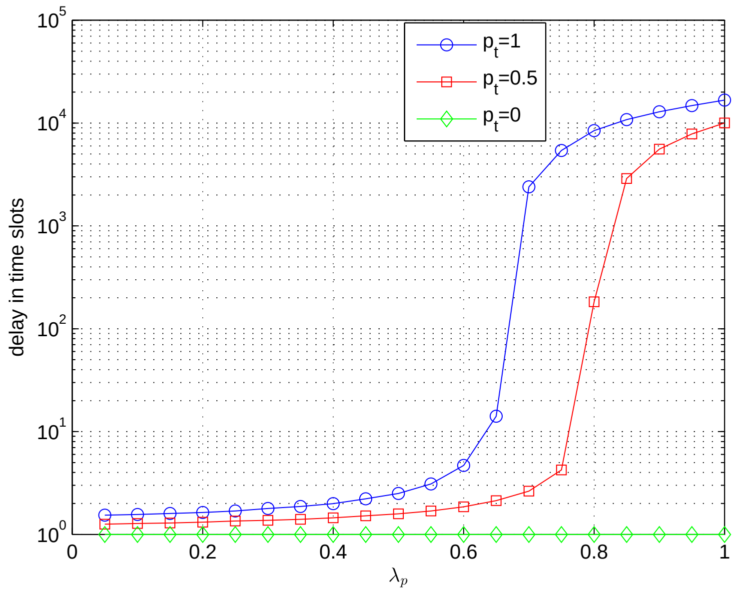
We have made the assumption that the SU has always energy and packets to send in order to find out the maximum interference that it causes on the PU, as well as the maximum service rate the SU can have. The interference is measured in terms of packet delay.

Simulating this scheme in Matlab we obtained the results presented in Figure 3.1. As we can see, for any $p_s < 1$ the PU's packets suffer very high delays and the Q_p becomes unstable. On the other hand, the SU can not sense the channel in every slot because of the energy limitations it has. Therefore, we added the probability of direct channel access p_t. By adding this probability, when the SU decides not to sense the channel instead of accessing it directly it will access it with probability p_t. In this case we have lower probability of direct access, which results in less interference for the PU and also less energy consumption for the SU because the latter will remain idle in a time slot with probability $(1 - p_s) \cdot (1 - p_t)$.

The simulations results for this scheme are presented in Figure 3.2. We can see that this scheme behaves better than the previous one in terms of primary packet delays for any value of λ_p. Although, the service rate for the SU is lower for low values of λ_p it is interesting that for high values of λ_p the service rate for the SU is higher and the interference it causes on the PU lower compared with the corresponding results of the previous scheme. In addition, as we can see from the results presented in Figure 3.2b, this scheme becomes unstable for high values of λ_p witch demonstrates the need for a different access scheme.



(a)



(b)

Figure 3.2: Service rate for SU (a) and averages delays of PU's packets (b) for different values of p_t and for $p_s = 0.5$.

3.2 The Adaptive Access Scheme

From the results we obtained and discussed in section 3.1, we understand that the best for the SU is to behave differently according to the PU arrival rate. When the value of λ_p is low, it's better for the SU to directly access the channel, because the probability of causing a collision is very low. Also, in that case,it is better to avoid sensing in order not to waste energy and time. For high values of λ_p, the SU should remain idle with high probability in order to avoid collisions and to conserve energy, otherwise it should sense the channel and not access it directly. This means that the values of p_s and p_t must be computed dynamically, according to the PU's arrival rate.

3.2.1 Computing p_s and p_t

The authors of [3] proposed an access scheme for a SU in cognitive radio systems utilizing the available PU feedback information. The SU employs a random access scheme where the access probability of the SU is adjusted according to the PU feedback state. Their objective was to find an access probability a_s for the SU to maximize its throughput while keeping the PU's queue stable. They have shown that this access probability is:

$$a_s = \min\left(\frac{1-\lambda_p}{2\lambda_p}, 1\right), \quad (1) \quad \text{where} \quad \frac{1-\lambda_p}{2\lambda_p} < 1 \quad \text{which occurs when} \quad \lambda_p > \frac{1}{3}$$

They also have shown that the probability of Q_p being empty is:

$$\pi_o = 1 - \lambda_p - a_s\lambda_p \quad (2)$$

In our scheme, the probability that the SU will accesses the channel is given by:

$$a_s = p_s\pi_o + (1-p_s)p_t \quad \text{, therefore}$$

$$\overset{(2)}{\Longrightarrow} a_s = p_s(1-\lambda_p - a_s\lambda_p) + (1-p_s)p_t$$

For $\lambda_p \leq \frac{1}{3}$ we have $a_s = 1$ and:

$$\begin{aligned} p_s(1-\lambda_p-\lambda_p) + (1-p_s)p_t = 1 \\ \Rightarrow p_s(1-2\lambda_p) + (1-p_s)p_t = 1 \\ \Rightarrow p_t = \frac{1-p_s(1-2\lambda_p)}{1-p_s} \qquad (3) \end{aligned}$$

But for p_t we must have $p_t \geq 0$:

$$\Rightarrow \frac{1-p_s(1-2\lambda_p)}{1-p_s} \geq 0$$
$$\Rightarrow 1-p_s(1-2\lambda_p) \geq 0$$
$$\Rightarrow p_s \leq \frac{1}{1-2\lambda_p}$$

And for p_t we must have $p_t \leq 1$:

$$\Rightarrow \frac{1-p_s(1-2\lambda_p)}{1-p_s} \leq 1$$
$$\Rightarrow 1-ps(1-2\lambda_p) \leq 1-p_s$$
$$\Rightarrow 1-p_s+2\lambda_p p_s \leq 1-p_s$$
$$\Rightarrow 2\lambda_p p_s \leq 0$$
$$\Rightarrow \boxed{p_s = 0} \qquad (4)$$

(3) $\overset{(4)}{\Longrightarrow}$

$$p_t = \frac{1-0(1-2\lambda_p)}{1-0}$$
$$\Rightarrow \boxed{p_t = 1}$$

For $\lambda_p > \frac{1}{3}$ we have $a_s = \frac{1-\lambda_p}{2\lambda_p}$ and:

$$p_s(1-\lambda_p-a_s\lambda_p)+(1-p_s)p_t = a_s$$
$$\Rightarrow p_s(1-\lambda_p-\frac{1-\lambda_p}{2\lambda_p}\lambda_p)+(1-p_s)p_t = \frac{1-\lambda_p}{2\lambda_p}$$
$$\Rightarrow p_s(2-2\lambda_p-1+\lambda_p)+2(1-p_s)p_t = \frac{1-\lambda_p}{\lambda_p}$$
$$\Rightarrow p_s(1-\lambda_p)+2(1-p_s)p_t = \frac{1-\lambda_p}{\lambda_p}$$
$$\Rightarrow 2(1-p_s)p_t = \frac{1-\lambda_p-p_s(1-\lambda_p)\lambda_p}{\lambda_p}$$
$$\Rightarrow p_t = \frac{\frac{(1-\lambda_p)(1-\lambda_p p_s)}{\lambda_p}}{2(1-p_s)}$$

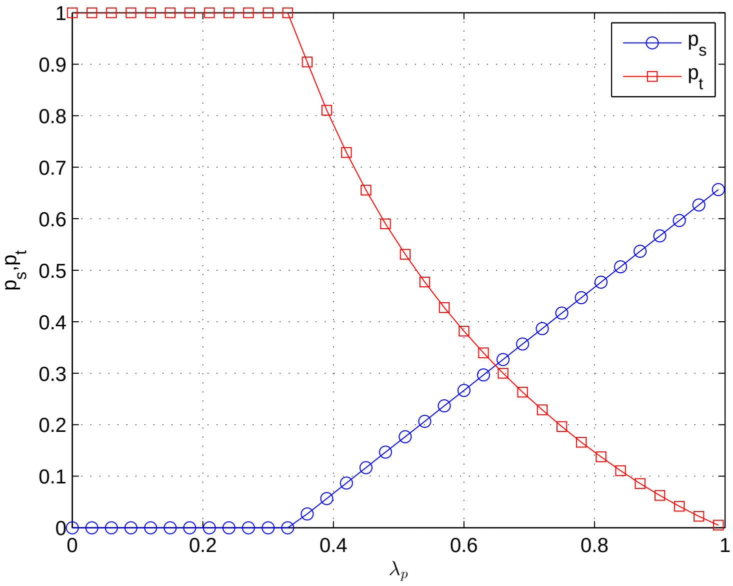


Figure 3.3: The values that p_s and p_t are taking according to λ_p

$$\Rightarrow p_t = \frac{(1-\lambda_p)(1-\lambda_p p_s)}{2\lambda_p(1-p_s)} \qquad (5)$$

But for p_t we must have $p_t \geq 0$:

$$\Rightarrow \frac{(1-\lambda_p)(1-\lambda_p p_s)}{2\lambda_p(1-p_s)} \geq 0$$

which is true for any $\quad 0 \leq \lambda_p \leq 1 \quad$ and $\quad 0 \leq p_s \leq 1$

And for p_t we must have $p_t \leq 1$:

$$\Rightarrow \frac{(1-\lambda_p)(1-\lambda_p p_s)}{2\lambda_p(1-p_s)} \leq 1$$

$$\Rightarrow (1-\lambda_p)(1-\lambda_p p_s) \leq 2\lambda_p(1-p_s)$$

$$\Rightarrow 1-\lambda_p p_s - \lambda_p + \lambda_p^2 p_s \leq 2\lambda_p - 2\lambda_p ps$$

$$\Rightarrow \lambda_p^2 p_s + \lambda_p p_s \leq 3\lambda_p - 1$$

$$\Rightarrow p_s \lambda_p(\lambda_p + 1) \leq 3\lambda_p - 1$$

$$\Rightarrow p_s \leq \frac{3\lambda_p - 1}{\lambda_p(\lambda_p+1)}$$

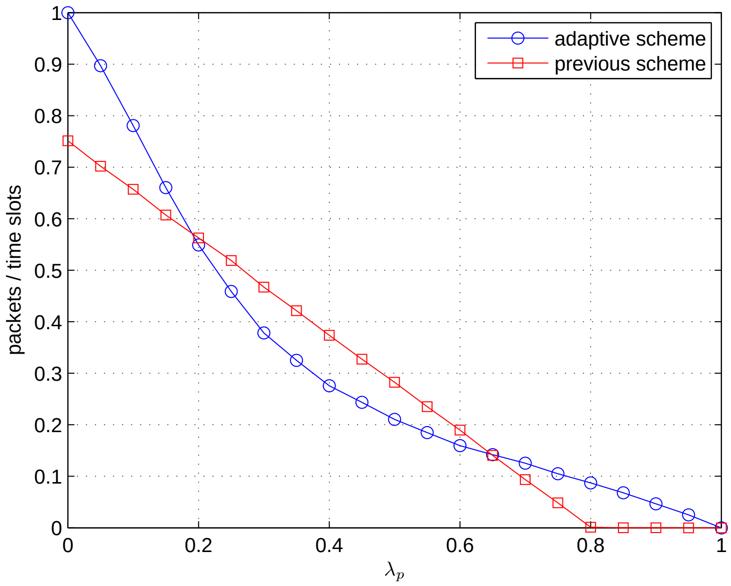
For $\lambda_p \in [\frac{1}{3} \quad 1]$ the function $f(\lambda_p) = \dfrac{3\lambda_p - 1}{\lambda_p(\lambda_p + 1)}$ is increasing and its minimum value is $f(\frac{1}{3}) = 0$. We set $\boxed{p_s = \lambda_p - \frac{1}{3}}$ (6) and we can then easily prove that $\lambda_p - \frac{1}{3} \leq \dfrac{3\lambda_p - 1}{\lambda_p(\lambda_p + 1)}$ for any $\lambda_p \in [\frac{1}{3} \quad 1]$.
Substituting this value of p_s in (5) we have:

$$
\begin{aligned}
p_t &= \frac{(1-\lambda_p)(1-\lambda_p(\lambda_p - \frac{1}{3}))}{3\lambda_p(1-\lambda_p+\frac{1}{3})} \\
&= \frac{(1-\lambda_p)(1-\lambda_p^2+\frac{1}{3}\lambda_p)}{2\lambda_p(\frac{4}{3}-\lambda_p)} \\
&= \frac{1-\lambda_p^2+\frac{1}{3}\lambda_p-\lambda_p+\lambda_p^3-\frac{1}{3}\lambda_p^2}{\frac{8}{3}\lambda_p-2\lambda_p^2} \\
&= \frac{\lambda_p^3-\frac{4}{3}\lambda_p^2-\frac{2}{3}\lambda_p+1}{\frac{8}{3}\lambda_p-2\lambda_p^2} \\
\Rightarrow p_t &= \frac{3\lambda_p^3-4\lambda_p^2-2\lambda_p+3}{8\lambda_p-6\lambda_p^2} \qquad (7)
\end{aligned}
$$

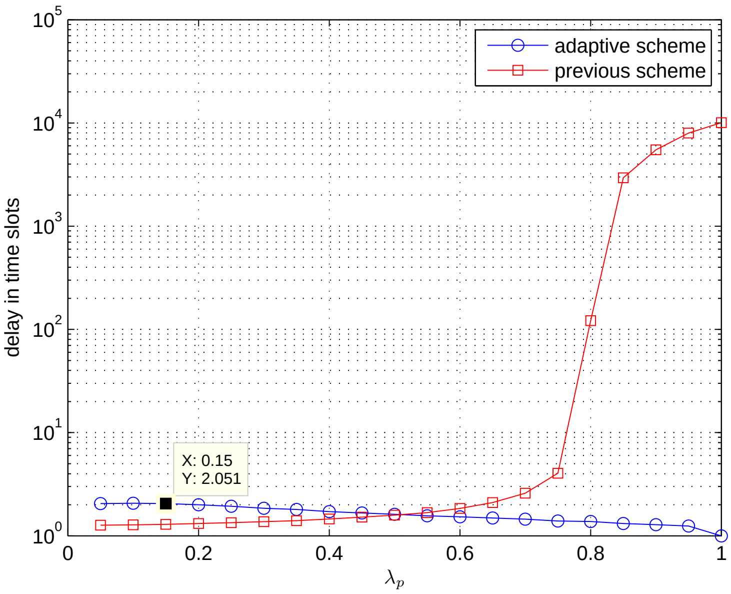
In Figure 3.3 we show how the values of p_s and p_t change as λ_p varies. By using them in our simulation, we can see in Figure 3.4a the service rate of the SU and in Figure 4.2a the average delays of the PU's packets. In the above mentioned figures we compare the results for the adaptive access scheme with those of the non-adaptive one in section 3.1, when $p_s = 0.5$ and $p_t = 0.5$.
From the results we can see that the service rate for the SU is lower than the one in the non-adaptive scheme for intermediate values of the primary arrival rate. Although, the delays that the PU packets suffer in the non-adaptive scheme are extremely high for large values of the primary arrival rate, in the adaptive scheme the delays are low which means that the adaptive scheme provides the QoS needed for the PU.

3.2.2 Estimation of the Primary Arrival Rate

Assuming that the SU has no information about the primary user arrival rate, in order to manage its adaptive behaviour we need to make an estimation of the primary arrival



(a)



(b)

Figure 3.4: Service rate for SU (a) and primary packet delays (b) with the adaptive access scheme compared with the previous scheme when $p_s = 0.5$ and $p_t = 0.5$

rate (λ_p^{est}). A simple estimate of λ_p is obtained by using the PU feedback that the SU can overhear. We compute λ_p^{est} by keeping in a First In First Out (FIFO) queue the latest PU feedback. In our simulation we use a queue with capacity of 50 nodes. To estimate λ_p, we sum the number of ACKs in the queue and we divide it by the capacity of the queue:

$$\lambda_p^{est} = \frac{\text{Number of ACKs}}{\text{Size of Queue}} \quad (8)$$

.

In Figure 3.5 we can see the λ_p^{est} compared with the actual λ_p in a simulation of 10^5 time slots. The values of λ_p have been assumed random, following the uniform distribution over [0,1], and these values remain constant for a random period of time between 0 and 10^4 time slots, also following a uniform distribution.

Although the above estimation (8) seems to be adequate, in our study we will estimate λ_p as:

$$\lambda_p^{est} = \frac{\text{Number of ACKs} + \text{Number of NACKs}}{\text{Size of Queue}} \quad (9)$$

By taking into account the NACKs, we provide the SU information about the amount of interference it caused to the PU in the past time slots. This enables our estimator to much faster track the instantaneous big increases of λ_p. Also, by overestimating λ_p according to the number of collisions that have occurred in the past time slots, we force the SU to be less aggressive. From the results in Figure 3.6 we can see the λ_p^{est} compared with the actual λ_p in a simulation of 10^5 time slots.

3.2.3 Random Primary Arrival Rate

In this section we test the the adaptive access scheme in a situation with a random primary arrival rate which takes values from a uniform distribution in [0,1]. The value of λ_p remains constant for a random period of time between 0 and 10^4 time slots. We are using the values of p_s, p_t as computed in section 3.2.1 and the λ_p^{est} as in section 3.2.2 and we test our system in the cases that the arrival rate is following the Bernoulli process and the Poisson process. The following simulations are referring to the worst case scenario where the SU has always energy and packets to send. The results of these simulations

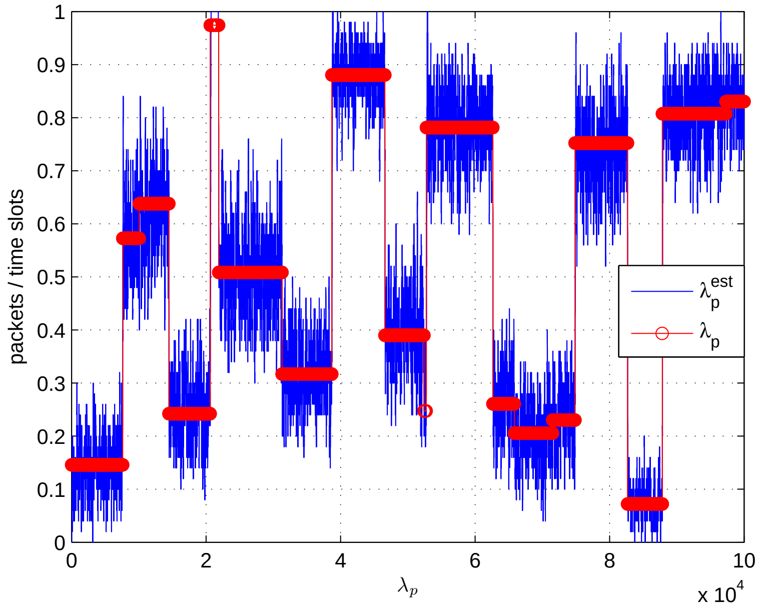


Figure 3.5: λ_p^{est} for random values of λ_p

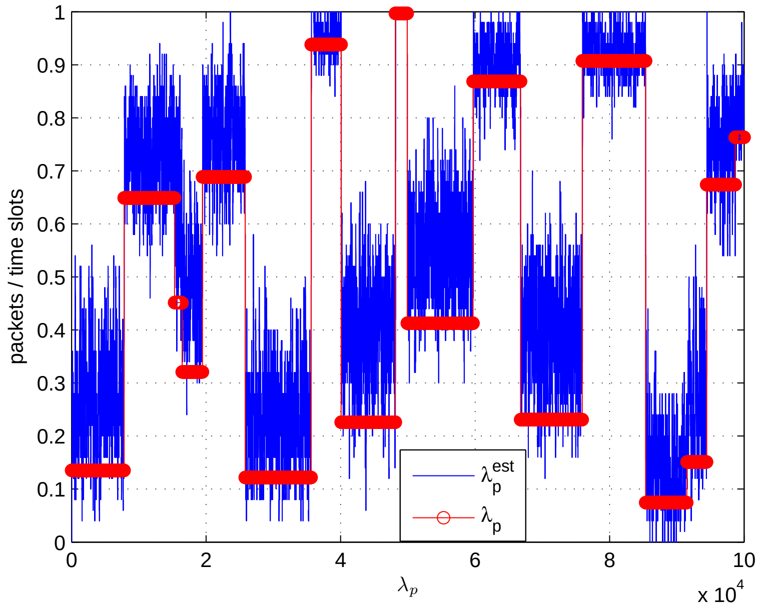
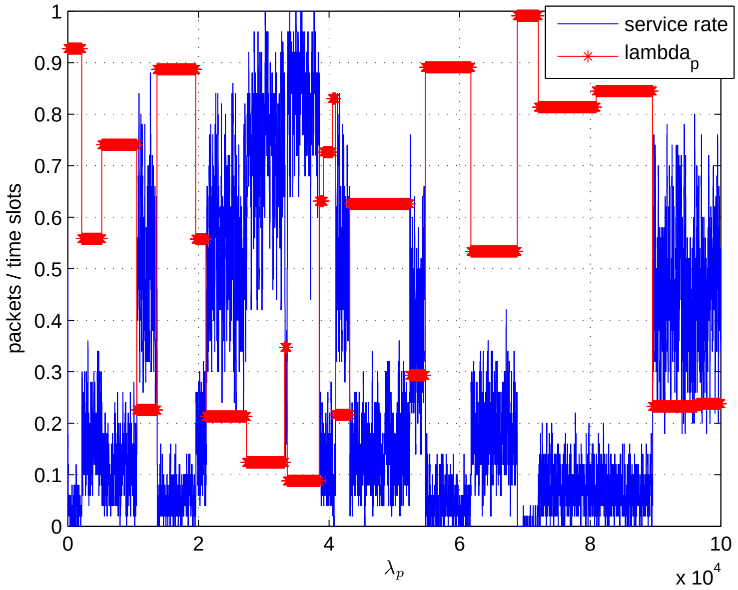
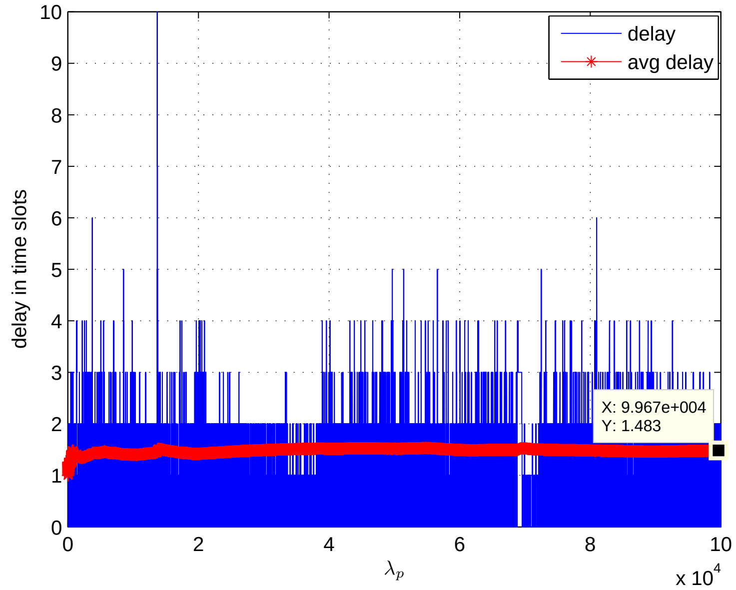


Figure 3.6: λ_p^{est} when tacking into account the collisions



(a)



(b)

Figure 3.7: Service rate for SU (a) and primary packet delays (b) when the primary arrival rate is following a Bernoulli Process

are showing the maximum interference that the PU suffers and the maximum service rate that the SU can achieve.

3.2.3.1 Bernoulli Arrivals

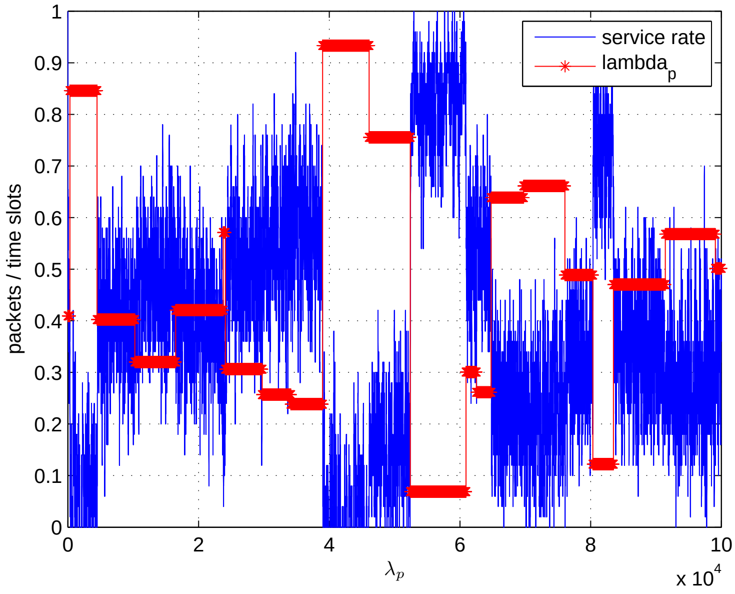
In Figure 3.7a we can see the service rate for the SU for different values of λ_p and in Figure 3.7b we can see the actual delays and the average delay that the PU's packets are suffering. Also in table 3.1 we can see some statistical results obtained from 1000 independent simulation runs.

Average arrival rate for PU	0.498
Average service rate for SU	0.313
Average delay of PU's packets (in time slots)	1.511
Percentage of PU's packets that suffered collision	20.11%
Percentage of time slots that SU remains idle	38.07%
Percentage of time slots that SU decides to sense the channel	27.89%
Percentage of time slots that SU decides to access directly the channel	34.04%

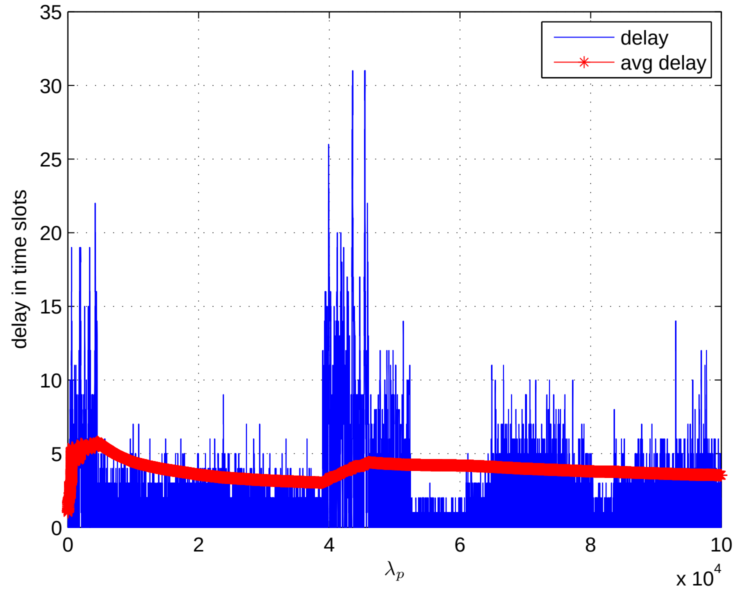
Table 3.1: Statistical results from 1000 independent simulation runs when the primary arrival process is Bernoulli

3.2.3.2 Poisson Arrivals

In order to make the performance evaluation more realistic, we changed the PU arrival process from Bernoulli to Poisson. The results of our simulations are presented in Figure 3.8 and as expected, are worse than those with a Bernoulli arrival process, in terms of PU's packet delay, because of the burstiness characteristics of the Poisson arrival process.



(a)



(b)

Figure 3.8: Service rate for SU (a) and primary packet delays (b) when the primary arrival process is Poisson

In Figure 3.8a we can see the service rate obtained by the SU for different values of λ_p and in Figure 3.8b we can see the actual delays and the average delay that the PU's packets are suffering. Also in table 3.2 we can see some statistical results from 1000 independent simulation runs compared with the results we had when the primary arrival process was a Bernoulli one.

Arrival process:	Poisson	Bernoulli
Average arrival rate for PU	0.503	0.498
Average service rate for SU	0.372	0.313
Average delay of PU's packets (in time slots)	5.786	1.511
Percentage of PU's packets that suffered collision	18.19%	20.11%
Percentage of time slots that SU remains idle	15.83%	38.07%
Percentage of time slots that SU decides to sense the channel	54.50%	27.89%
Percentage of time slots that SU decides to access directly the channel	29.66%	34.04%

Table 3.2: Statistical results of 1000 independent simulation runs when the primary arrival process is Poisson compared with the corresponding ones when the primary arrival process is Bernoulli

3.3 The Proposed Access Scheme

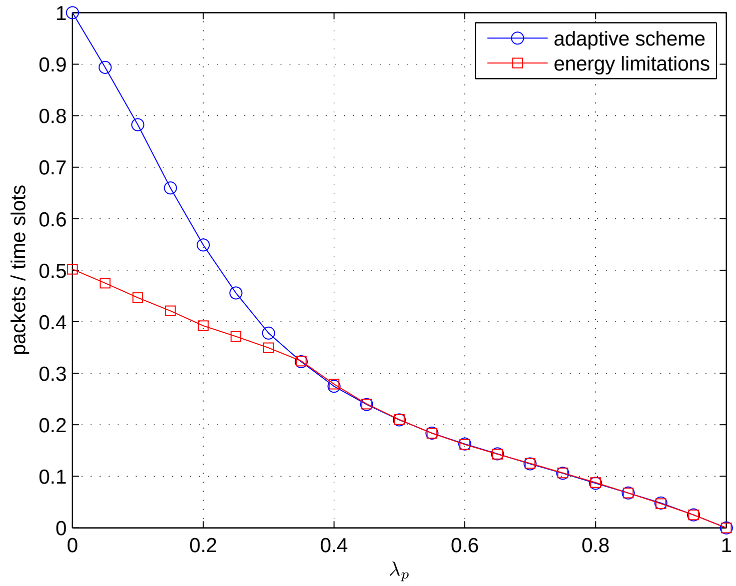
As we mentioned earlier, the Adaptive Access Scheme refers to the worst case scenario in terms of QoS achieved by the PU. By assuming that the SU always has energy and and data to send, we investigated the maximum interference that it can cause to the PU. However, an energy constrained user will occasionally run out of battery, we therefore propose and evaluate an access scheme for the case where the SU's energy queue Q_e has a finite capacity of 1000 energy units, the energy arrival rate is $\lambda_e = 0.5$, a packet transmission consumes one energy unit and the energy needed for sensing the channel is negligible. By adding these energy constraints, we obtain as expected some reduction in the SU's service rate and in the PU's packet delay as we can see from the results presented in Figure 3.9, compared to the corresponding results from the adaptive scheme without energy limitations.

In the adaptive access scheme we computed the amount of energy that the SU consumes for a given λ_p and we found the minimum arrival rate of energy packets λ_e that the SU should have in order not to run out of battery and therefore to be able to exploit the most of the available spectrum holes. In Figure 3.10 we can see the diagram for λ_e according to λ_p.

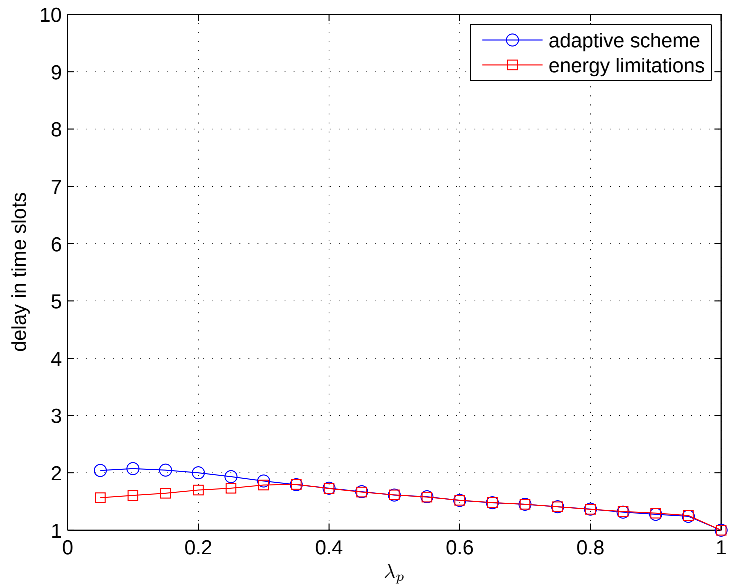
The reduction in service rate, due to energy limitations, makes necessary that the SU should adopt an energy saving policy when needed. For example when the energy level in the battery is low and the primary arrival rate is high, there is high probability of collision meaning that most probably the SU will waste energy trying to access a busy channel. On the other hand, when the primary arrival rate is low, there is high probability for a successful secondary transmission meaning that the SU should access the channel regardless of its remaining energy.

Next, we consider a system that has one PU and one SU. The channel is slotted in time and a slot duration equals to the packet transmission time. The PU and SU have infinite size buffer queues Q_p and Q_s to store fixed-length packets. The SU has also a finite size buffer queue Q_e to store harvested energy from the environment. The arrivals at Q_p, Q_s and Q_e are assumed independent Bernoulli random processes with means λ_p, λ_s and λ_e, respectively. In order to simplify our analysis and presentation we further assume that a packet will be transmitted correctly if only one user is transmitting and the probability of error in sensing the channel is negligible.

As in the adaptive scheme, the PU accesses the channel whenever it has a packet to send. The SU monitors the PU feedback and makes use of the PUs automatic repeat request in order to decide how to act. He may overhear an acknowledgment (ACK) if the PU sends a packet correctly, a negative acknowledgment (NACK) if the PU fails to send



(a)



(b)

Figure 3.9: Service rate for SU (a) and PU's average packet delay (b) compared with the adaptive access scheme without energy limitations

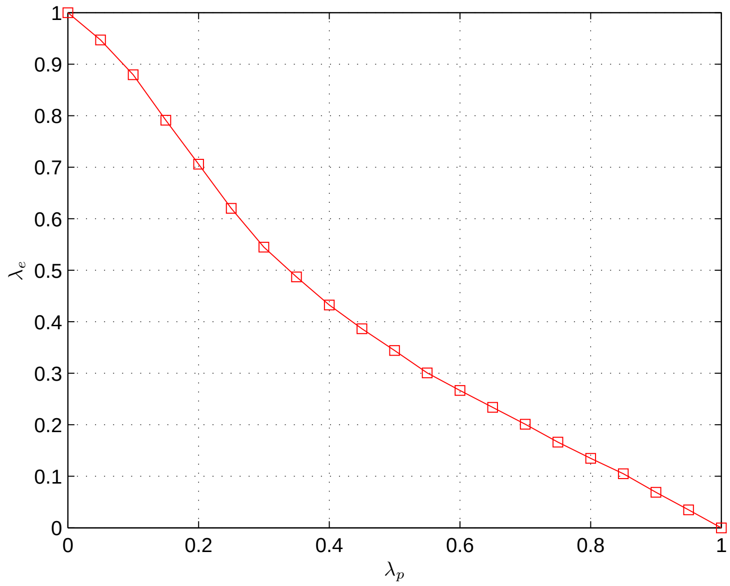


Figure 3.10: The minimum value of energy arrival rate λ_e that the SU needs in order to achieve maximum throughput as a function of λ_p

a packet, or nothing if the PU remains idle (does not have a packet to send). If a NACk is overheard, the SU remains idle during the next time slot. Otherwise, it will estimate the PU's arrival rate, as we discussed in section 3.2.2, and according to that estimation and the energy remaining in its battery it will act as follows:

- If $0 \leq \lambda_p^{est} \leq 1/3$, the SU will behave as in the adaptive scheme
- If $1/3 < \lambda_p^{est} \leq 2/3$:
  - If the energy level is greater than 50%, the SU will behave as in the adaptive scheme
  - If the energy level is between 20% and 50%, it will reduce the probability of direct channel access by 50%
  - If the energy level is less than 20%, the probability of direct channel access is set equal to zero
- If $\lambda_p^{est} > 2/3$:

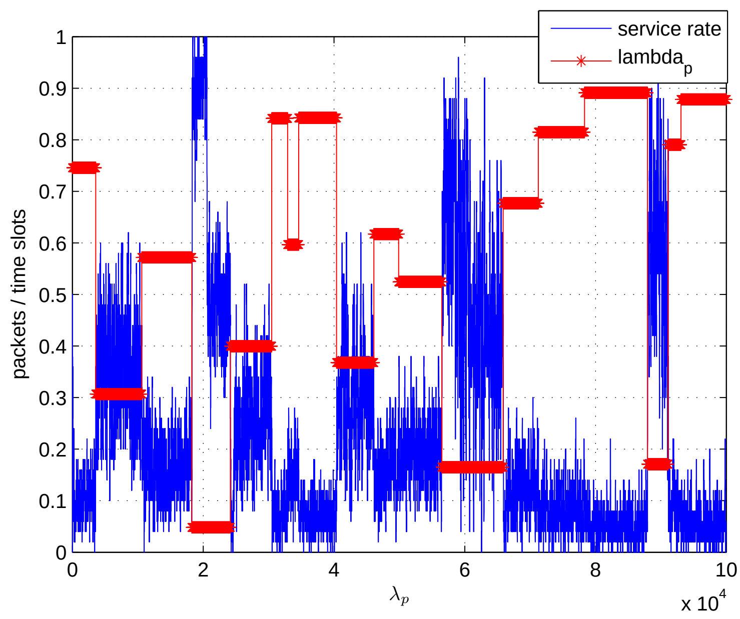
- If the energy level is greater than 50%, it will reduce the probability of direct channel access by 50%
- If the energy level is between 20% and 50%, it will set the probability of direct channel access to zero
- If the energy level is less than 20%, it will set the probability if direct access and the probability of sensing equals to zero (the SU remains idle with probability one)

3.3.1 Random Primary Arrival Rate

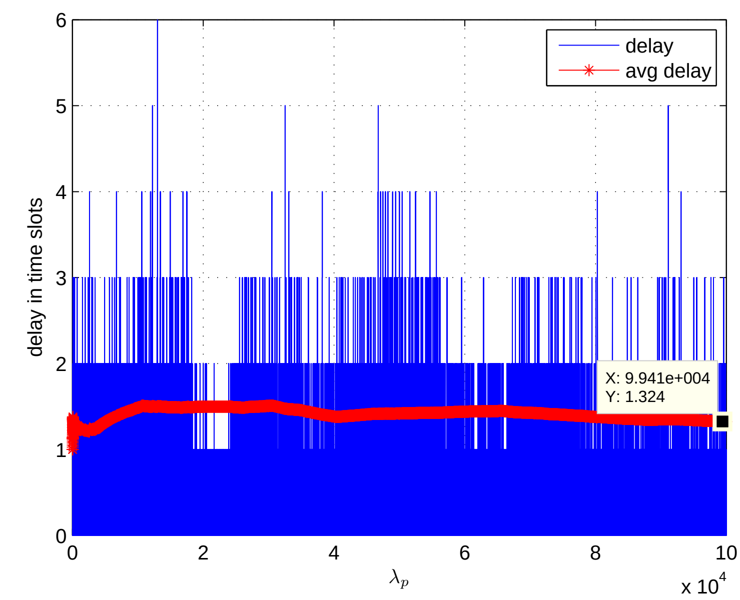
As in the case of the adaptive access scheme, we are testing our scheme in a situation with random primary arrival rate which takes values from a uniform distribution in [0,1]. The value of λ_p remains constant for a random period of time between 0 and 10^4 time slots and the primary arrival process is assumed to follow the Bernoulli and Poisson processes.

Access Scheme:	Proposed	Adaptive
Average arrival rate for PU	0.499	0.498
Average service rate for SU	0.261	0.313
Average delay of PU's packets (in time slots)	1.395	1.511
Percentage of PU's packets that suffered collision	16.91%	20.11%
Percentage of time slots that SU remains idle	45.49%	38.07%
Percentage of time slots that SU decides to sense the channel	27.04%	27.89%
Percentage of time slots that SU decides to access directly the channel	27.47%	34.04%

Table 3.3: Statistical results from 1000 independent simulation runs compared with those of the adaptive scheme when the primary arrival process is Bernoulli



(a)



(b)

Figure 3.11: Service rate for SU (a) and primary packet delays (b) when the primary arrival process is Bernoulli

3.3.1.1 Bernoulli Arrivals

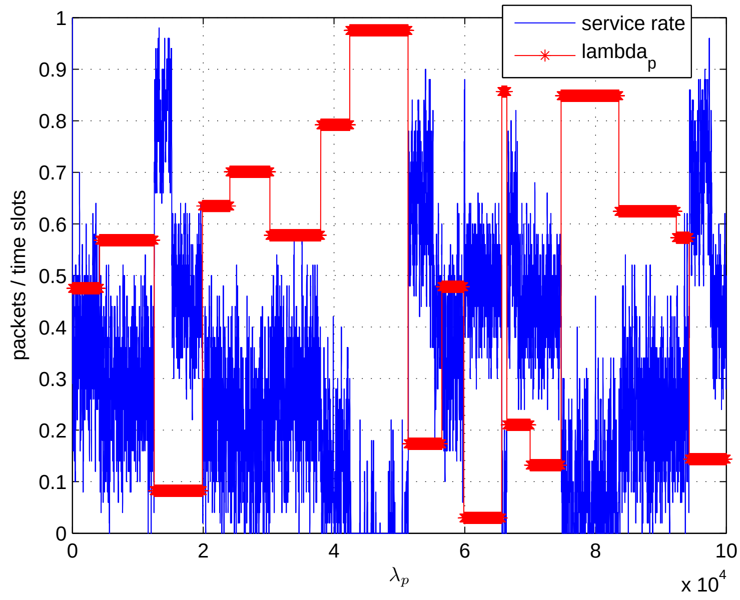
The simulation results for this case are presented in Figure 3.11. In Figure 3.11a we can see the service rate for the SU for different values of λ_p and in Figure 3.11b we can see the actual delays and the average delay that PU's packets are suffering. Also in table 3.3 we can see some statistical results from 1000 independent simulation runs compared with the corresponding results for the adaptive access scheme.

As we can see from the above comparison, with the proposed scheme we have a 16.61% reduction on SU's service rate but only a 7.68% reduction on the PU's average packet delay. Also, we can see that the the number of time slots that the SU remains idle increases, and that the number of PU direct channel accesses as well as the number of collisions decreases.

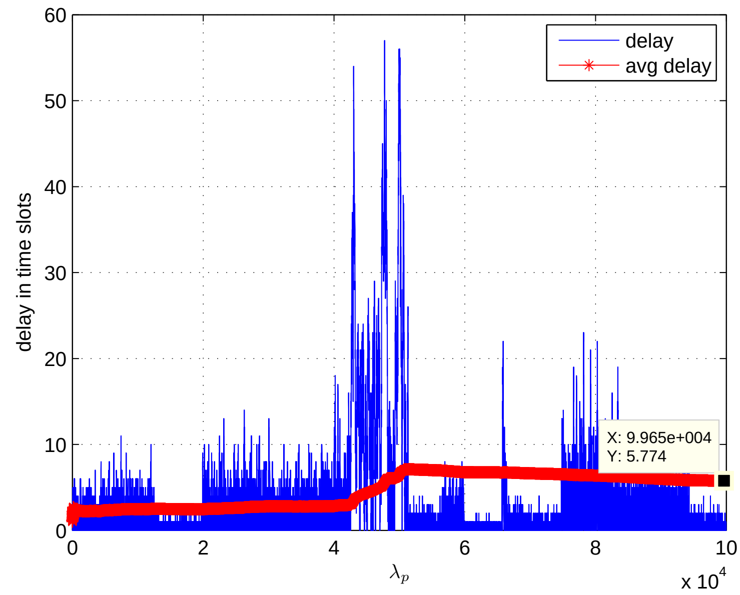
3.3.1.2 Poisson Arrivals

The simulation results for this case are presented in Figure 3.12 and as it was expected, are worse than those with a Bernoulli arrival process in terms of PU's packet delays, because of the burstiness characteristics of the Poisson arrival process.

In Figure 3.12a we can see the service rate for the SU for different values of λ_p, and in Figure 3.12b we can see the actual delays and the average delay that PU's packets are suffering. Also in table 3.4 we can see some statistical results from 1000 independent simulation runs compared with the results we had in the adaptive access scheme. From this comparison we observe a reduction of 14.52% on the SU' service rate and a small reduction of 2.76% on the PU's packet average delay . Also, we can see that there is an increase in the number of the slots that the SU remains idle and a decrease in the number of direct channel accesses and in number of collisions for the SU.



(a)



(b)

Figure 3.12: Service rate for the SU (a) and PU packet delays (b) when the primary arrival process is Poisson

Access Scheme:	Proposed	Adaptive
Average arrival rate for PU	0.501	0.503
Average service rate for SU	0.318	0.372
Average delay of PU's packets (in time slots)	5.626	5.786
Percentage of PU's packets that suffered collision	17.08%	18.19%
Percentage of time slots that SU remains idle	22.47%	15.83%
Percentage of time slots that SU decides to sense the channel	52.49%	54.50%
Percentage of time slots that SU decides to access directly the channel	25.05%	29.66%

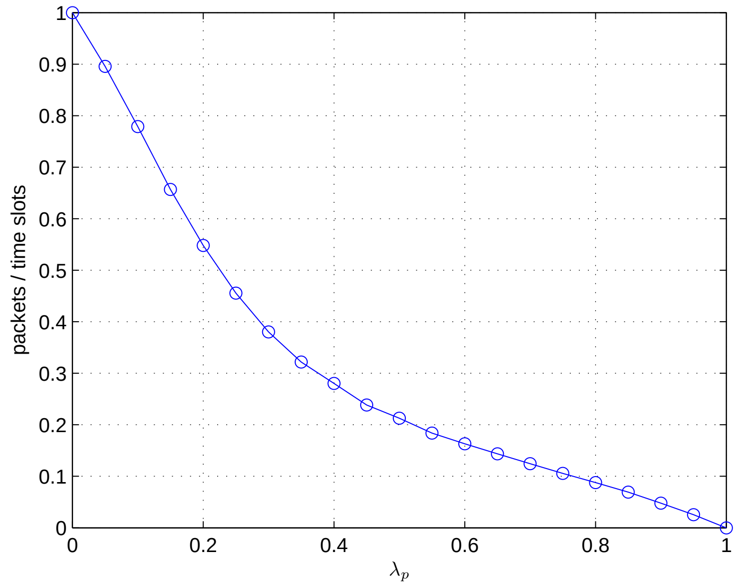
Table 3.4: Statistical results from 1000 independent simulation runs compared with those of the adaptive scheme when the primary arrival process is Poisson

Chapter 4

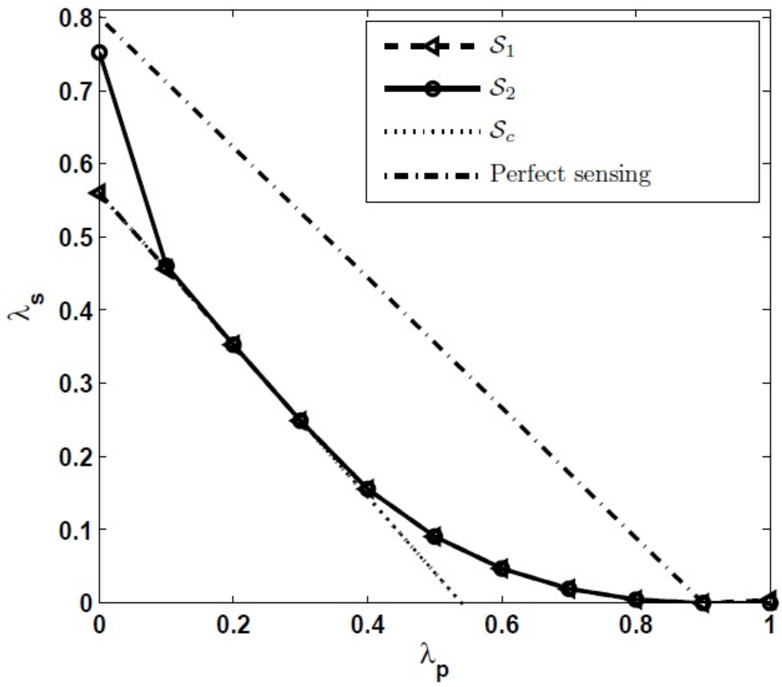
Access Scheme Comparative Performance Evaluation

In the previous chapter we proposed a feedback based random access scheme and we presented simulation based performance results for it. In this chapter we will investigate whether or not, these results are satisfactory. In order to achieve this, we will try to compare our adaptive access scheme with two similar access schemes from the literature. The two schemes we will compare with, do not have any energy limitations and their authors assumed that the SU has always packets to send. Therefore, we will put into comparison the adaptive access scheme as described in section 3.2, instead of the proposed access scheme presented in section 3.3, because of the energy limitations that the proposed access scheme possesses.

The authors of [2] proposed four different access schemes for a system consisting of one PU and one SU. In the *conventional spectrum sensing* scheme (S_c), the SU senses the channel for τ seconds to detect the possible activities of the PU. If the PU is sensed to be idle the SU transmit the packet with probability one. If the channel is sensed to be busy the SU does not transmit. In the *random access without sensing scheme* S_0, the SU accesses randomly the primary channel without employing any sensing technique. In the *first proposed random access scheme* S_1, the SU randomly access the channel if and only if the PU is sensed to be idle. Finally, in the *second proposed access scheme* S_2,



(a)



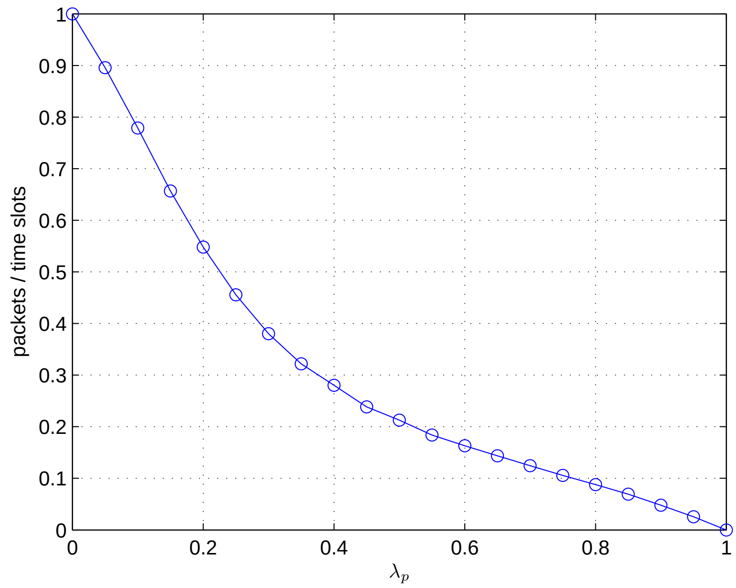
(b)

Figure 4.1: Service rate for the SU for our adaptive access scheme (a) compared with the scheme in [2] (b)

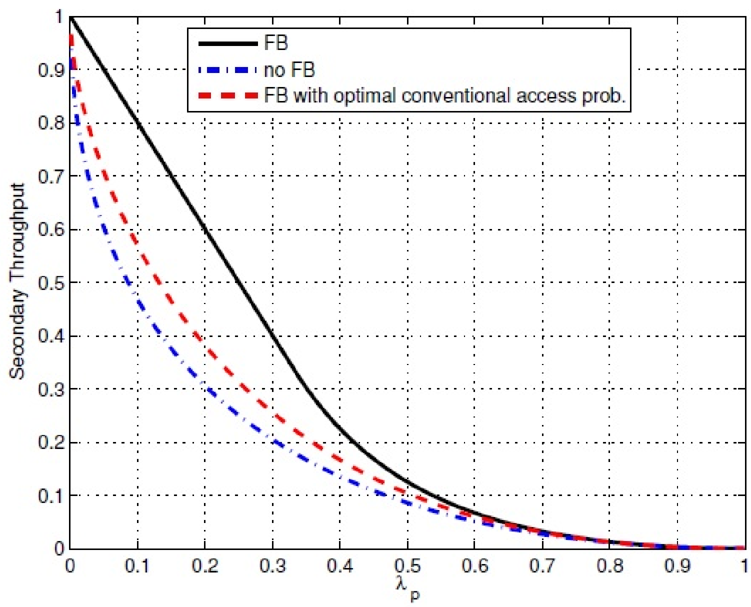
which we will compare with, the SU senses the primary channel to detect the possible activities of the PU and accesses the channel randomly with some probability a_s if the channel is sensed to be free, or with probability b_s if the channel is sensed to be busy. The authors take into account the probabilities of missed detection, false alarm and the probability of packet reception error. In Figure 4.1 we can see the comparison. Clearly, the maximum service rate for the SU achieved in [2] is less than ours in part because of the probabilities of error that have been taken into account. We point out that in their scheme, the SU senses the channel in each time slot, which means that their scheme transmits packets of shorter length than our scheme. Furthermore the scheme in [2] guarantees that the PU's queue, Q_p, is stable. However, no delay analysis of the PU's packets is provided.

The authors of [3] proposed tow random access schemes for a system consisting of one PU and one SU. In the first access scheme, named *conventional access scheme*, the SU accesses the channel with probability a_s independent of the PU activity. The second access scheme, named feedback-based access scheme, is the one we will compare with. In the *feedback-based access scheme*, the PU accesses the channel whenever it has a packet to send. The SU utilizes the available primary feedback and it randomly accesses the channel with some probability a_s. Also, the authors in [3] assumed that a packet will be delivered correctly if only one user is transmitting on the channel. We can see the performance comparison in Figures 4.2 and 4.3.

From the service rate figures we can see that for $\lambda_p < 1/3$, in our scheme the service rate is slightly lower, while for $\lambda_p > 1/3$ it is higher. We must mention here that for $\lambda_p > 1/3$, in our scheme, the SU will sense the channel with probability $p_s = \lambda_p - 1/3$, while there is no sensing in the scheme we compare with. On the other hand, comparing the delay figures, it is clear that in our scheme the PU suffers less interference thus achieving better QoS. Furthermore, we must point out that our scheme uses an estimation of λ_p while the scheme in [3] we compare with assumes that λ_p is known.

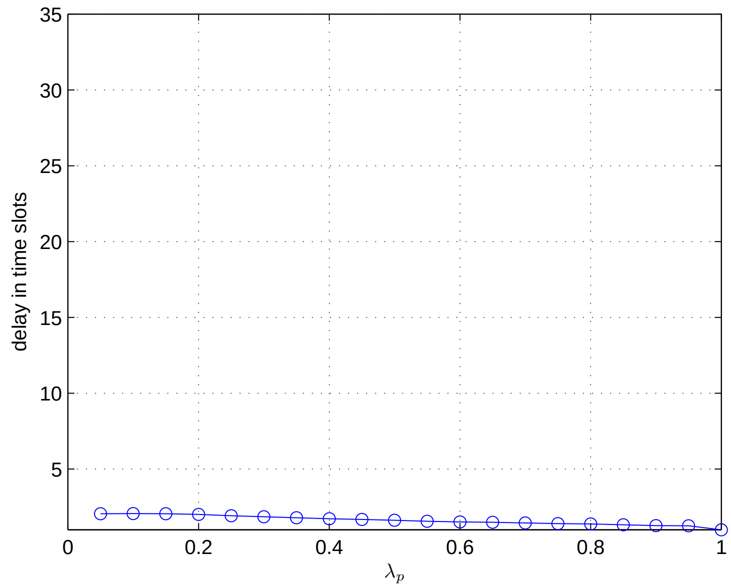


(a)

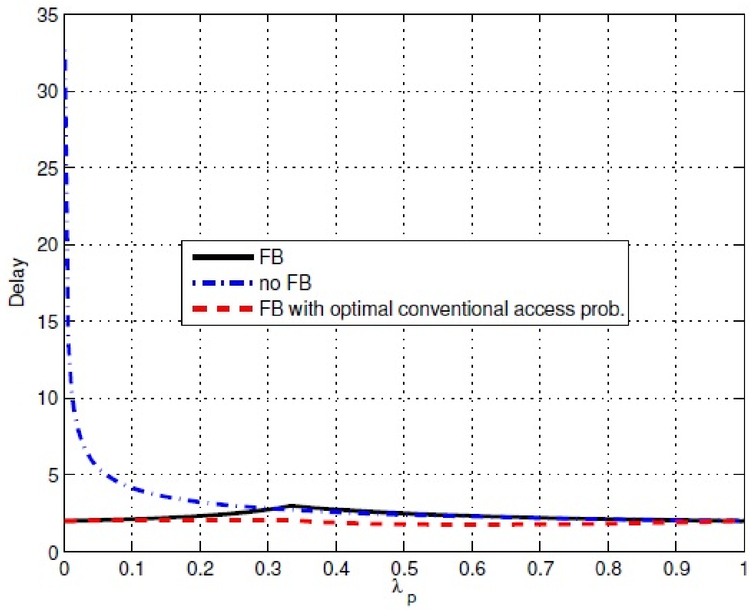


(b)

Figure 4.2: Service rate for the SU in our adaptive access scheme (a) compared with the service rate in the scheme in [3] (b)



(a)



(b)

Figure 4.3: PU's average packet delay in our adaptive access scheme (a) compared with the corresponding average packet delay in [3] (b)

Chapter 5

Conclusion

The need for resolving spectrum's underutilization problem leads to the opportunistic spectrum access. Secondary users are searching for and exploiting local and instantaneous spectrum holes under the constraint that the primary users obtain a certain quality of service.

In this thesis we proposed an access scheme (section 3.2) for a SU with energy harvesting capabilities, which incorporates random spectrum sensing and random channel access. The sensing and access probabilities are dynamically computed based on an estimation we make on the PU arrival rate. Via simulations we found the maximum service rate that the SU can achieve as well as the maximum interference that it causes to the PU. We tested the performance of our scheme in the cases where the primary arrival process was following the Bernoulli and Poisson processes and we compared the corresponding results. We also proposed an adaptive scheme (section 3.3) where the SU employs an energy saving policy in order to better manage the remaining energy in it battery. Finally, we compared the performance of our scheme with the performance of two similar schemes presented in the literature.

5.1 Future Work

For future work we would like to see our scheme tested in a wireless network with more realistic traffic arrivals and energy harvesting techniques. Also, it would be interesting to investigate more intelligent energy management policies for the SU.

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