Chapter 1

Introduction

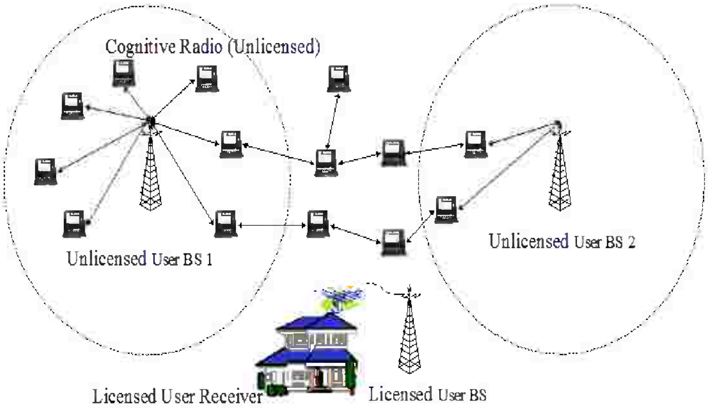

FIGURE 1.1: Cognitive radio network

The electromagnetic radio spectrum is a natural resource, the use of which by transmitters and receivers is licensed by governments. In November 2002, the Federal Communications Commission (FCC) published a report prepared by the Spectrum-Policy Task Force, aimed at improving the way in which this precious resource is managed in the United States [1]. The task force was made up of a team of high-level, multidisciplinary professional FCC staffeconomists, engineers, and attorneysfrom across the commissions bureaus and offices. Among the task force major findings and recommendations, the second finding on page 3 of the report is rather revealing in the context of spectrum utilization: In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access. Indeed, if we were to scan portions of the radio spectrum including the revenue-rich urban areas, we would find that [2]:

1) some frequency bands in the spectrum are largely unoccupied most of the time;

2) some other frequency bands are only partially occupied;

3) the remaining frequency bands are heavily used.

The underutilization of the electromagnetic spectrum leads us to think in terms of spectrum holes, for which we offer the following definition: A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user. Spectrum utilization can be improved significantly by making it possible for a secondary user (who is not being serviced) to access a spectrum hole unoccupied by the primary user at the right location and the time in question. Cognitive radio has opened up a new way of sensing and utilizing precious wireless spectrum resources.

Cognitive radio is a dynamically reconfigurable radio that can adapt its operating parameters to the surrounding environment, which has been made feasible by recent advances such as software-defined radio and smart antennas. Using such cognitive radio devices enables flexible and agile access to the wireless spectrum, which can, in turn, improve efficiency in spectrum utilization significantly. In particular, cognitive radio is considered key to resolving the soon-to-occur spectrum scarcity problem. Under The spectrum policy mentioned above, each spectrum band is assigned to a designated party, which is given an exclusive spectrum usage right for a specific type of service and radio device. We can provide a clear definition of cognitive radio as following: 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:

a) highly reliable communications whenever and wherever needed;

b) efficient utilization of the radio spectrum.

Six key words stand out in this definition: awareness, intelligence, learning, adaptivity, reliability, and efficiency. Implementation of this far-reaching combination of capabilities is indeed feasible today, thanks to the spectacular advances in digital signal processing, networking, machine learning, computer software, and computer hardware.

In addition to the cognitive capabilities just mentioned, a cognitive radio is also endowed with reconfigurability. This latter capability is provided by a platform known as software-defined radio, upon which a cognitive radio is built. Software-defined radio is a practical reality today, thanks to the convergence of two key technologies: digital radio, and computer software [3].

For reconfigurability, a cognitive radio looks naturally to software-defined radio to perform this task. For other tasks of a cognitive kind, the cognitive radio looks to signal-processing and machine-learning procedures for their implementation. The cognitive process starts with the passive sensing of RF stimuli and culminates with action. There are three on-line cognitive tasks:

1) Radio-scene analysis, which encompasses the following:

- estimation of interference temperature of the radio environment;
- detection of spectrum holes.

2) Channel identification, which encompasses the following:

- estimation of channel-state information;
- prediction of channel capacity for use by the transmitter

3) Transmit-power control and dynamic spectrum management.

Tasks 1) and 2) are carried out in the receiver, and task 3) is carried out in the transmitter. It is apparent that the cognitive module in the transmitter must work in a harmonious manner with the cognitive modules in the receiver. In order to maintain this harmony between the cognitive radios transmitter and receiver at all times, we need a feedback channel connecting the receiver to the transmitter. Through the feedback channel, the receiver is enabled to convey information on the performance of the forward link to the transmitter. The cognitive radio is, therefore, by necessity, an example of a feedback communication system. another benefit of feedback channel is that it introduces redundancy in the system, in the form of copies of the same message transmitted in subsequent time slots. The idea of exploiting this redundancy is investigated in [20] where several protocols are proposed, in which the secondary transmitter collects side-information about the primary message in the first primary transmission, which is exploited to relay the primary message, if a retransmission occurs. While in [21], the authors introduce a mechanism where the secondary receiver can perform interference cancellation during the whole primary feedback window by decoding the primary message, thus enhancing its own outage performance. In particular, they investigate a Backward Interference Cancellation mechanism in which the secondary receiver buffers the secondary transmissions that underwent outage due to primary interference, and attempts to recover them once the knowledge about the primary message becomes available due to decoding operation in a future instant.

As mentioned before, detecting the PU activity (spectrum sensing) plays an important role in cognitive radio implementation. SUs need to monitor the available spectrum (or a portion of it, if there are energy consumption constraints) in order to be able to detect spectral holes. A typical way to address the problem is to look for primary transmissions by using a signal detector. Spectrum sensing is an essential functionality of cognitive radios. In general, spectrum sensing techniques can be classified into three categories: energy detection [10], matched filter coherent detection [11], and cyclostationary feature detection [12]. While these classic signal detection techniques are well known, detecting primary transmitters in a dynamic wireless environment with noise uncertainty, shadowing, and fading is a challenging problem as articulated in [13]. SU takes the decision on whether to access the channel or not depending on the sensing information, and this is known as the *interweave model*. In this case, the cognitive users are not aware of their impact on the primary network which can be severe if there are large number of sensing errors. One solution, that can alleviate the sensing errors consequences to some extent, is to allow the secondary users to exploit the feedback sent from the primary receiver to primary transmitter and secondary users act based on the overheard feedback as introduced in [14], where the secondary users overhear the automatic repeat request [15]. Leveraging the feedback information can provide a degree of coordination between the nodes of a cognitive radio network and a random access network[16]. This can result in a lower number of collisions, and hence, a reduction in energy consumption. In the model considered in [14] the PU has the authority to access the channel whenever it has a packet to transmit. The primary receiver sends an ACK over the feedback channel if the primary packet is successfully received. If the packet transmission fails, the primary receiver sends a NACK over the feedback link and consequently the primary user retransmits the packet again. In [17], a secondary transmission technique was introduced when the primary user retransmits the packet in order to manage the interference in retransmission-based wireless network. In [18], a collision-based model with feedback exploitation was considered where the secondary user backs off completely from accessing the channel upon hearing a NACK to allow for collision-free primary retransmission while the secondary user attempts to access the channel if an ACK/no feedback is overheard. In [19], the secondary user power is controlled on the basis of the primary user feedback link.

Another solution, that can alleviate the sensing errors consequences, is soft sensing. Soft sensing was introduced as a way to enhance the sensing reliability, as in [22], where the authors introduced a novel design in which the value of the test statistic is used as a confidence measure for the sensing outcome. This value is then used to specify a channel access probability for the secondary network. The access probabilities as a function of the sensing metric are obtained by solving an optimization problem formulated to maximize the secondary throughput given a constraint on the primary queue stability. The idea of soft sensing was first introduced in [23], however, the focus was on physical layer power adaptation to maximize the capacity of the secondary link.

Adaptive resource allocation is a promising technique to improve the performance of cognitive radio communication systems [24]. Using this technique, a cognitive radio node has the ability to change its transmission parameters based on active monitoring of several factors in the radio environment, such as radio spectrum, licensed users activity and traffic, and fading channel variations [25]. In particular, the transmission parameters of the secondary users, such as modulation level, transmit power and access probability, may be adjusted according to the channel variations while ensuring no harmful interference is caused to the PUs of the spectrum band. In this context, availability of channel state information at the cognitive transmitter was initially considered in [26], where the optimum adaptive power transmission scheme that achieves the shannon capacity [27], under fading and average transmit power constraint, was presented. The latter power optimization problem but subject to peak and average transmit power constraints was investigated in [28]. In [14], the access probabilities are optimized when the feedback exploitation technique and soft-sensing technique are used.

Cooperative diversity is a recently emerged technique for wireless communications that has gained wide attention [29]. As a new communication paradigm for wireless networks, the impact of cooperation at different network layers needs to be studied and understood. Most of the work on cooperative communications has focused on the physical layer aspects of the problem. Cooperation protocols for the single-relay case were developed and analyzed in [29], and later in [30] and [31] distributed spacetime codes were developed and analyzed for multiple-relay scenarios. In the previous works it was demonstrated that full diversity gain can be achieved by forming such virtual multiple-input multiple-output (MIMO) systems. The diversity-multiplexing tradeoff of cooperative diversity has been also explored in [32] using an information-theoretic framework. Achievable capacity and coding strategies for wireless relay channels have been considered recently in [33]. Cooperative scenarios have been also introduced lately in cognitive radio in which a cooperating terminal relay packets for other terminals over the so called relay channel in order to increase the channel availability for its own packets [34]. A primary packet unsuccessfully transmitted by the PU and successfully transmitted to the SU is stored in a relay queue at the SU. On the other hand, the SU waits for the opportunity of an idle instant to transmit either the relayed packets or its own packets and in most studies priority is given to the relayed traffic in a way that guarantees QoS requirements of the PU. Randomized cooperative policies for cognitive radio system are also introduced in [35]. These scenarios have proved to enhance cognitive node performance.

Exploiting renewable energy resources from the environment, often termed as energy harvesting, offers an unattended operability of infrastructure-less wireless networks. There are various forms of energy that can be harvested including thermal, vibration, solar, acoustic, wind, and even ambient radio power [36], [37]. Despite the significant advancement of hardware technologies, the study on the network of nodes having energy harvesting capability is still in its infancy. In [38], the capacity of the additive white Gaussian noise channel with stochastic energy harvesting at the source was shown to be equal to the capacity with an average power constraint given by the average harvesting rate. However, like most of information-theoretic research, the result is obtained for point-to- point communication with an always backlogged source. When dealing with a network of nodes powered by non-rechargeable batteries, the common objectives were usually short-term goals such as maximizing the lifetime of the network while maintaining a certain degree of network connectivity [39]. The harvesting capability, however, enables us to consider steady-state performance measures such as the throughput, the fairness, and the stability of a network. Note that the packet queues are of interest for the stability study given the energy harvesting rates. In such context, the effect of the energy limitation on the performance of cognitive radio systems is studied in several works. In [40], the effect of this relative location on the average delay of both the primary and cognitive users is studied provided that the cognitive user has limited lifetime and it offers prioritized relaying capabilities to primary traffic that the PU failed to transmit. If the SU transmitter has a limited energy budget, forwarding the PU packets comes at the expense of the SU throughput since the SU wastes energy sending primary packets.

1.1 Contribution of the Thesis

In this thesis, we present the effect of energy harvesting and feedback exploitation on queues stability and delay of three different MAC systems. We first consider an interference-based model which can be thought of as a midway between the interweave model and the underlay model, in which the primary and secondary users coexist. It can also be thought of as a "hybrid", i.e., interweave/underlay [41]. The cognitive radio link inherits the channel sensing process from the interweave model, while co-existing with the PU is inherited from the underlay model. In our model, we allow the SU(s) to access the channel even if the PU is either sensed to be active or known to be active through the overheard primary feedback, assuming NACK messages are received by the transmitting user with certainty. The SU(s) will have different access probabilities that depend on the PU state. The protection for the PU will be provided by optimizing the SU access probabilities. We optimize the selection of the access probabilities based on maximizing the secondary network throughput subject to some PUs quality of service (QoS) constraints.

In this model, we will consider two PU QoS constraints, namely, the PU queue stability and the PU average delay. In the PU queue stability constraint the secondary network throughput is maximized subject to the constraint that the PU queue is stable, i.e., the queue length does not grow to infinity; while in the PU average delay constraint, we set a maximum on the average PU packet delay. Note that if an average PU delay constraint is employed this will guarantee that the PU queue is stable. We show that the interference-based model provides higher SU throughput than the collision-based model. Under the constraint of stable PU queues, the average delay is larger, however, in our interference-based model, when we fix a limit on the average PU delay for both systems, we observe an improvement in the SU throughput.

Then, we focus on the effect of finite energy sources and energy harvesting on the stability of a random access network. We consider a network with two nodes. Each having a queue to store packets, and a battery to store energy. The process of energy consumption from the battery during transmission, and its replenishment through energy harvesting is modeled by considering the battery as a queue with arrival and service rates determined by the energy harvesting and consumption rates, respectively. When a node has packets in its packet queue, it will attempt to transmit the packet at the head of the queue with some access probability if there is enough energy in its battery queue. If the transmission is successful, the packet is dropped from the queue. In case of a collision, the destination stores the collided packets, and sends negative acknowledgement (NACK). Making use of the NACK message, one node refrains from any transmission attempts, while the other node retransmits the collided packet. The destination can then use the retransmitted packet and the stored collided packets to recover the two packets involved in the collision. Therefore, the two nodes are served in two transmission attempts, but the retransmitting node has used more energy in the process.

In a random access network, the stability analysis usually involves interacting queues. For the slotted ALOHA protocol, the stability region is characterized for the case of $M = 2$ and $M = 3$ interacting queues as well as the case of $M > 3$ with symmetric arrivals. The stability region for the general case of $M > 3$ with asymmetric arrivals is still an open problem and only inner achievable bounds are known. Recently, many researches have considered the problem of interacting queues in different contexts. For example, [42] considers the problem of interacting queues in a TDMA system where a relay is used to help the source nodes in forwarding their lost packets. In [43], the stability of interacting queues under a random access protocol in the context of Cognitive Radio Network was derived. In [44], the stability region of two interacting queues under random access protocol where the two queues harvest energy was characterized. Other works can be found in [45, 46], where derivations of the stability regions in the context of different cognitive radio networks were considered. One of the solution to solve the interacting queues difficulty is *stochastic dominance technique*. In [47], the exact stability region was obtained for the twonode case and for the cases with more than two nodes with symmetric arrival rates and transmission probabilities using the stochastic dominance technique. A sufficient condition for general asymmetric cases with more than two nodes was obtained in the paper as well. [48], the stochastic dominance technique was further used to obtain an improved inner bound, i.e., a sufficient condition, for general asymmetric cases. In [49], the necessary and sufficient conditions were derived but the conditions can only be evaluated up to the three-node case. The concept of instability rank was introduced in [50] and used to further improve the inner bound for general cases.

Finally, we study the effect of finite energy sources and energy harvesting on the stability and the average packet delay of cooperative multiple access for cognitive radio system. We focus on the class of randomized cooperative policies, whereby the SU admits the PU's packet and serves it with certain probabilities. Besides, we study the effect of energy limitation on the way that tuning the admission and service probabilities affects the stable throughput of the PU and SU. We also use the moment generating function to characterize the upper bound of the average delay encountered by the packets of the PU and the SU. Note that, the analysis involves an interaction between packet queues and the battery. We solved this difficulty in this case and in the previous one by using stochastic dominance technique.

1.2 Thesis Organization

The rest of the thesis is organized as follows. In chapter 2 we analyze a cognitive relaying network in which the SU exploits the PU feedback with interference based model. Chapter 3 presents the effect of finite energy sources and energy harvesting on the stability of a random access network. Chapter 4 investigates the effect of finite energy sources and energy harvesting on the stability and the average packet delay of cooperative multiple access for cognitive radio system. Finally, our work is concluded in chapter 5.