Chapter 5

Conclusions and Future Work

In this thesis, we studied the effect of energy harvesting and feedback exploitation on the stability region and the delay for different systems. We characterized the benefits of exploiting the feedback information which provides some sort of coordination. Such coordination decreases the consumed energy and increases the throughput of the systems. We also identified the loss in the stability region and the delay prolongation that occurs due to the energy restriction.

We first considered a cognitive spectrum access scheme in which the secondary user benefits from overhearing the primary user feedback. The SU(s) accesses the channel through a random access scheme and the access probabilities are selected based on the overheard primary feedback as well as the sensing decisions. The SUs are allowed to access the channel as long as they do not violate a primary user quality of service constraint. In this case, we have considered two primary user quality of service constraints, namely, the primary user queue stability constraint and the PU average packet delay constraint. We have considered an interference based model in which simultaneous transmissions from the primary and the secondary users do not always result in a packet loss. In the case, we select the secondary user access probabilities to maximize the secondary user throughput under the primary user quality of service constraint. Our results show significant gains of the interference based model if compared to the collision-based model. These gains decrease as the effect of the interference increases.

Then, we studied the stability of queues in a random access network where the nodes have rechargeable finite energy sources, and collision resolution capability through the exploitation of the feedback information. Collision resolution is achieved by allowing only one node to retransmit after the collision, while the other node refrains from retransmission. The receiver then uses the collided packets and the retransmitted packet to recover the two collided packets. The rechargeable energy sources are modeled as queues, along with the data queues at each nodes they form an interacting of queues. The stability region of this system is characterized through the use of the dominant system analysis approach. The stability region obtained is compared with that of TDMA system and a random access network without energy constrained, and the reduction in the stability region due to the finite energy is determined.

Finally, we analyzed the queues stability and delay of cooperative multiple access for cognitive radio systems in which the SU has a rechargeable finite energy source. The system in consideration has a randomized service policy whereby the SU probabilistically selects to serve either the queue of its own data or the relay queue. Moreover, the relayed packet that fails to reach the destination is admitted to the relay queue with some probability upon being successfully decoded by the SU. The rechargeable energy source is modeled as a queue, along with the data queues at the SU they form an interacting system of queues. The stability region of this system is characterized through the use of the dominant system analysis approach, and the reduction in the stability region due to the energy finiteness as well as the effect of the system parameters on this region are characterized. Moreover, an upper bound on the average packet delay encountered by the packets of the PU and SU is characterized using the moment generating function. The stability region and delay obtained is compared with that of the system without energy constraint.

As a future work, three issues can be investigated:

1- In the cognitive radio system in which the SU exploits the feedback information of the primary receiver, we have studied the system for single user, single SU and single PU, for simplicity. We can generalize this system i.e. study the system in which we have more than one SU.

2- For the random access network, we have studied the system for two nodes that have data queues and batteries for energy harvesting. As a future work, we can generalize this system i.e. study the system in which we have more than two nods.

3- In the delay analysis of cooperative multiple access for cognitive radio systems in which the SU has a rechargeable finite energy source, we can provide a proof of the delay behaviour in which the average delay curves for both systems (with and without energy limitations) are coincided.

Appendix A

Proof of stability conditions of the dominant system 1 in random access system without energy limitation

A.1 Proof of Lemma 3.1

In this Appendix, we provide a proof for Lemma 3.1. We start by calculating the steady state distribution for the Markov chain shown in Fig. 3.2.

First, it is clear that $\epsilon_0 = 0$ since the queue can never be in a retransmission state while being empty. Writing the balance equation around 1_R, we have

$$\epsilon_1 = \lambda_1 p_1 p_2 \pi_0 + (1-\lambda_1)\, p_1 p_2 \pi_1. \tag{A.1}$$

Then around 0_F, we have

$$(\lambda_1 p_1 p_2 + \lambda_1 (1-p_1))\pi_0 = (1-\lambda_1)\,\epsilon_1 + (1-\lambda_1)\, p_1 (1-p_2)\pi_1. \tag{A.2}$$

Substituting for ϵ_1 from (A.1) into (A.2), and after some manipulations, we can get

$$\pi_1 = \frac{\lambda_1 (1-p_1+\lambda_1 p_1 p_2)}{p_1 (1-\lambda_1)(1-\lambda_1 p_2)}\pi_0. \tag{A.3}$$

Substituting from (A.3) into (A.1), we get $\epsilon_1 = \frac{\lambda_1 p_2}{1-\lambda_1 p_2}\pi_0$.

Writing the balance equation around 1_F, we have

$$\begin{aligned} &(1-\lambda_1 p_1 (1-p_2) - (1-\lambda_1)(1-p_1))\, \pi_1 = \\ &\lambda_1 \pi_0 + \lambda_1 \epsilon_1 + (1-\lambda_1)\,\epsilon_2 + (1-\lambda_1)\, p_1 (1-p_2)\, \pi_2. \end{aligned} \tag{A.4}$$

Around 2_R, we have $\epsilon_2 = \lambda_1 p_1 p_2 \pi_1 + (1-\lambda_1)\, p_1 p_2 \pi_2$.

$$\epsilon_2 = \lambda_1 p_1 p_2 \pi_1 + (1-\lambda_1)\, p_1 p_2 \pi_2. \tag{A.5}$$

To get the relation between π_1 and π_2, we can substitute for the values of ϵ_1, π_0 and ϵ_2 from equations (A.1), (A.2) and (A.5), respectively in equation (A.4); after some tedious manipulation, we get

$$\pi_2 = \frac{\lambda_1 (1-p_1+\lambda_1 p_1 p_2)}{p_1 (1-\lambda_1)(1-\lambda_1 p_2)}\pi_1. \tag{A.6}$$

Substituting from (A.6) into (A.5), we get $\epsilon_2 = \frac{\lambda_1 p_2}{1-\lambda_1 p_2}\pi_1$. Note that the Markov chain is repeating from stage 2 till the end. For $k \geq 2$, we have the following relations.

$$\pi_k = \frac{\lambda_1 (1 - p_1 + \lambda_1 p_1 p_2)}{p_1 (1 - \lambda_1)(1 - \lambda_1 p_2)}\pi_{k-1}. \tag{A.7}$$

$$\epsilon_k = \frac{\lambda_1 p_2}{1 - \lambda_1 p_2}\pi_{k-1}. \tag{A.8}$$

The last relation can be used to prove the following relation between ϵ_k and ϵ_{k-1}.

$$\epsilon_k = \frac{\lambda_1 (1 - p_1 + \lambda_1 p_1 p_2)}{p_1 (1 - \lambda_1)(1 - \lambda_1 p_2)}\epsilon_{k-1}. \tag{A.9}$$

The steady state distribution can now be written as follows.

- $\epsilon_0 = 0$, $\epsilon_1 = \frac{\lambda_1 p_2}{1-\lambda_1 p_2}\pi_0$, and $\epsilon_k = \rho^{k-1}\epsilon_1$, $k \geq 2$.
- $\pi_k = \rho^k \pi_0$, $k \geq 1$ and $\rho = \frac{\lambda_1(1-p_1+\lambda_1 p_1 p_2)}{p_1(1-\lambda_1)(1-\lambda_1 p_2)}$.

This steady state distribution can be easily checked to satisfy the balance equation at any general state (details are omitted since it is a rather straightforward, yet very tedious, procedure).

To get the value of the steady state probabilities, we apply the following normalization requirement.

$$\begin{aligned} &\sum_{k=0}^{\infty}(\pi_k + \epsilon_k) = 1 \\ &\rightarrow \pi_0 + \sum_{k=1}^{\infty}(\pi_k + \epsilon_k) = \pi_0 \left(1 + \frac{\lambda_1 p_2}{1 - \lambda_1 p_2}\right)\sum_{k=0}^{\infty}\rho^k = 1, \end{aligned} \tag{A.10}$$

where $\rho = \frac{\lambda_1(1-p_1+\lambda_1 p_1 p_2)}{p_1(1-\lambda_1)(1-\lambda_1 p_2)}$ as defined above.

Note that for the steady state distribution to exist, i.e. to have π_0 to be non zero, then we must have $\rho < 1$, which is the stability condition for Q_1 in this dominant system. Therefore, the stability condition can be stated as

$$\rho < 1 \ \rightarrow \lambda_1 < \frac{p_1}{1 + p_1 p_2}. \tag{A.11}$$

From the normalization condition in (A.10), we can get the value of π_0 as $\pi_0 = \frac{p_1 - \lambda_1(1+p_1 p_2)}{p_1(1-\lambda_1)}$.

In Dominant System 1, Q_2 will be served in both states denoted by the subscript F and R in Fig. 3.2. Hence, the service rate, μ_2, for Q_2 in Dominant System 1 is given by

$$\mu_2 = p_2(1-\lambda_1 p_1)\pi_o + \sum_{k=1}^{\infty} p_2(1-p_1)\pi_k + \sum_{k=1}^{\infty} \epsilon_k. \tag{A.12}$$

where in the 0_F state, Q_2 is served if Q_2 decides to access the channel when Q_1 decides not to access the channel if it receives a packet at the start of the time slot or there is no arrival for the packet; for the other first transmission states, Q_2 will be served if it decides to access the medium, which occurs with probability p_2, and Q_1 decides not to access the medium, which occurs with probability $(1-p_1)$; for retransmission state, Q_2 will be served with probability one. After some manipulation, we can write the expression for μ_2 as

$$\mu_2 = \frac{p_2(1-\lambda_1 p_2 + \lambda_1^2 p_2 - \lambda_1)}{(1-\lambda_1)}. \tag{A.13}$$

For the stability of Q_2, we must have

$$\lambda_2 < \mu_2 = \frac{p_2(1-\lambda_1 p_2 + \lambda_1^2 p_2 - \lambda_1)}{(1-\lambda_1)}. \tag{A.14}$$

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