The Impact of Delay on the Decisions of a Cognitive Radio Engine

[1]Hamed Asadi, [2]Haris Volos, [1]Michael M. Marefat, and [1]Tamal Bose
[1]Dept. of Electrical and Computer Engr. The University of Arizona, Tucson, AZ 85721-0104
{hasadi, marefat, tbose}@arizona.edu
[2]DENSO International America Inc., San Jose, CA 95110-1342
volos@ieee.org

***Abstract*—In this paper, we investigate the effect of delay in the decision-making and operation of a cognitive radio engine. In particular applications, such as deep space communications, communicating with space exploration equipment throughout the solar system the roundtrip delay can be minutes to hours. The CE is faced with the task of making decisions that it will not know of their outcome after a considerable delay. In this paper, we provide the system model, and we evaluate various decision strategies taking into account the expected channel states during the transmission period. Our results show that the expected and variance of the amount of delayed feedback have a significant impact on the decision-making and performance of the system.**

I. Introduction

In all types of the communications, it takes some time that a message travels from a transmitter to a receiver. In addition, it takes some time that the receiver process the data and notifies the transmitter that the message is received correctly or not. In result, whenever a transmitter set a new configuration (modulation type, coding, MIMO techniques, power, ...) and start to transmit, there will be some delay, until it can have an evaluation about the quality of its decision. Depending on the distance and protocols of a communication system, the amount of delay varies significantly. Nevertheless, in almost all of the designed CEs for wireless communications [1]–[10], there is a strong assumption which assumes the CE will see the result of its decision immediately and perfectly represent the actual conditions. However, in an actual implementation, the observed data, i.e., the received feedback of CE's decisions or the estimated channel conditions, are most likely to arrive with differnet amount of delays. Therefore, it is of paramount importance to estimate the effect of these degradations on the CE's performance. For example, in link adaptation, when the CE transmits a packet by specific configuration, it's assumed that the CE will receive an acknowledgment (ACK/NACK) immediately; however, even in the LTE-Advanced (3GPP Release 10) [11]–[13] it's assumed that the ACK/NACK will be sent after 4 resource blocks. Each resource block is assumed to take 0.5 milliseconds. Therefore, the CE needs to wait at least for 2 milliseconds to be able to take advantages of the previous decision's result. For other communication systems, the problem is even more serious. For instance, in long-range HF communications, the CE needs to make multiple decisions without receiving any feedback on previous decisions. Furthermore, the behavior of the delay can be different for various actions. It's possible that the CE receives the ACK/NACK of a packet which is sent after the other packet in advance.

In this paper, we studied the effect of delay on wireless communication systems by evaluating the relationship between the amount of delay and CE's performance. Then, we analyzed the impact of delay on the performance of various CE algorithms.

The first contribution of this paper lies in fully modeling the delayed feedback scenario in wireless communication systems. More specifically, we propose a general stochastic model for the CE's decision-making when it's operating in a delayed feedback environment.

And the second contribution of this work is analyzing the delays' effects on some of the proposed CE algorithms in the literature, and finding the most effective parameters on their performance.

This paper is organized as follows: Section II provides an overview of the delayed feedback model for the CE algorithms, which we are going to use in the paper. Section III analyzes the effect of delay in different wireless communication protocols. Finally, Section IV provides concluding remarks.

II. Problem Formulation

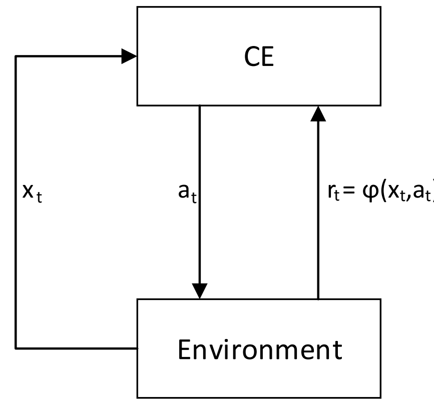
To provide a model for delayed feedback scenarios, we consider a general reinforcement learning model with delayed rewards [14]. This model is pretty similar to the CE model which we used in [1], [6], [15] without delay. The general CE model needs to make sequential decisions based on information about the channel scenarios, conditions of the radio (power level, capabilities, etc.), and its own experience which will specifically be exploited from its experience database. Formally, given a current channel scenario x_t, which is a vector of all features of channel scenario at time step *t*, a set of possible communication configurations *A*, which is a complete set of adjustable communication parameters (i.e. modulation type, coding rate, antenna technique, etc.), we will have a set of reward functions $\Phi \subset \{\varphi : X \times A \rightarrow R\}$, and possible reward values *r*, for different time steps *t*.

The CE senses the environment and receives x_t, then chooses an action a_t from the list of possible actions A while the environment picks a reward function $\varphi_t \in \Phi$ at the same time. Finally, the CE receives a reward value r_t from the reward function $\varphi_t(x_t, a_t)$. The CE algorithm aims to maximize the expected reward $\sum_{t=1}^{n} \varphi_t(x_t, a_t)$ which in the link adaptation problem definition [1] is equal to maximizing $\sum_{t=1}^{n} r_t(n \geq 1)$. To compare the performance of different CE algorithms, we are going to use the concept of *regret*. The *regret* of a CE is equal to the difference between the maximum possible reward in each time step with the reward of an action which is taken by the operated CE algorithm.

$$\Delta_n = sup_{a \in A} \sum_{t=1}^{n} \varphi_t(x_t, a(x_t)) - \sum_{t=1}^{n} \varphi_t(x_t, a_t) \quad (1)$$

A CE is consistent if it achieves the average reward of the best possible action. To compare the performance of different CE algorithms, we are not only interested in how fast the average regret can be made to converge to 0, $E[\Delta_n]/n \rightarrow 0$, but we are also interested in minimizing the amount of Δ_n that will result in higher throughput, in the case of maximizing throughput objective. Figure 1 shows the CE operation in the delayed case.

In this work, we assume that the delay at t_{th} time step (τ_t) is a constant value and is equal to τ_0 which depends on the communication's protocol.



Parameters: CE action set $\boldsymbol{A}$, possible channel scenarios $\boldsymbol{X}$, reward function $\boldsymbol{\phi}$: $\boldsymbol{X} \times \boldsymbol{A} \rightarrow \boldsymbol{\Phi}$,
At each time step *t=1, 2, ..., n:*

1. The radio senses the environment condition (channel scenario) $\boldsymbol{x_t} \in \boldsymbol{X}$
2. The CE will take an action $\boldsymbol{a_t} \in \boldsymbol{A}$, based on environment condition $\boldsymbol{x_t}$
3. The reward $\boldsymbol{r_t} = \boldsymbol{\varphi}(\boldsymbol{x_t}, \boldsymbol{a_t})$ is scheduled to be revealed after $\boldsymbol{\tau_t}$ time steps
4. The CE observes $\boldsymbol{R_t} = \{(\boldsymbol{t'}, \boldsymbol{r_{t'}}): \boldsymbol{t'} \leq \boldsymbol{t}, \boldsymbol{t'} + \boldsymbol{\tau_{t'}} = \boldsymbol{t}\}$, i.e., all the reward values scheduled to be revealed at time step t, together with their timestamps.

Fig. 1. CE operation under delayed modified from [14], [16], [17]

III. Effects of Delayed Feedback

In wireless communication protocols such as 3G [13], 4G [13], LTE [12], and LTE-Advanced [11] a specific time-frame for the ACK/NACK is considered. If a radio doesn't hear back from the receiver after a certain amount of time, it will assume that the packet is dropped. Therefore, in many of the wireless protocols, we can assume a constant delay for the CE operations where the CE needs to skip a particular number of decisions, based on the amount of delay.

The proposed non-delayed CE algorithms in the literature need to observe the feedback of the previous decision to be able to decide about the next configuration. Therefore, the CE process will be as follows:

- The CE observes the channel conditions at time t which is x_t.
- The CE takes an action a_t based on the current channel condition x_t.
- The CE waits until receives the feedback of transmitted packet at $t + \tau_t$.
- If the channel condition at $t + \tau_t$ is same as the channel condition at time t, the CE takes the next action $a_{t+\tau_t}$ based on the observed data.

The result of this approach will be lots of idle status of transmitter on the times that the CE is waiting to hear back from receiver about the status of transmitted data packets.

Weinberger & Ordentlich [18] proposed a delay handling strategy for the constant delay (τ_0) problem. In their approach, they assumed a non-delayed CE algorithm with τ_0 independent instants which are operating in sequences. They showed that the regret bound of the new algorithm is $(\tau_0)f(n/\tau_0)$ [19]. In this method, the regret bound of the delayed algorithm has a multiplicative effect on the regret bound of the individual non-delayed CE algorithm.

To be able to use Weinberger's strategy, during the operation of CEs, the channel conditions need to be constant. In wireless communications, we can assume that the channel impulse response is essentially invariant over the time frame, also known as coherence time. The coherence time is proportional to the Doppler spread, and the popular rule of thumb for calculating coherence time in modern digital communication is: [20]

$$T_C = \sqrt{\frac{9}{16\pi f_m^2}} = \frac{0.423}{f_m} \tag{2}$$

where f_m is the maximum doppler frequency and $f_m = \nu f_c/c$, where ν is the speed of the receiving or transmitting radio (assuming the other one is stationary), f_c is the radio carrier frequency, and $c = 3 \times 10^8 m/s$ is the speed of light.

To have a better understanding of the above formula, assuming the classic Jake's channel model, the envelope autocorrelation $R(\tau)$ of the channel is given by [21]:

$$R(\tau) = J_0(2\pi f_m \tau) \tag{3}$$

"The coherence time is the time duration over which two received signal have a strong potential for amplitude correlation" [22]. If we consider coherence time as the time over which the correlation coefficient is greater than 0.5 then the coherence time will be approximately [23] $T_c \approx \frac{9}{16\pi f_m}$, however this formula is too restrictive and 2 equation is more popular. Figure 2 depicts equation 3 versus delay time for $\nu \in [0,\ 1,\ 3,\ 10,\ 60]\ mph$ and $f_c = 2.4\,GHz$. Assuming correlation coefficient greater than 0.5, from Figure 2, it can be noticed that at walking speed ($3\ mph$), the channel condition can be considered stationary for slightly more than $20\ ms$. However, for the vehicle speed of $60\ mph$, this time will be just $3\ ms$.

Since the channel scenario can be assumed to be constant, in our CE model, the x_t will be constant for $t \leq T_C$. Therefore, the reward function $\varphi_t(x_t, a_t)$ will be based on the taken action a_t. As result, if the amount of delay will be less than $t \leq T_C$, we will be able to use Weinberger model for running the non-delay CE algorithms in delayed feedback scenarios.

The Weinberger's algorithm operates as follows. First, let's assume that the constant delay is equal to the time of the transmission of 4 packets or $\tau_0 = 4$ time steps. At the start of operation, an instance of a non-delayed CE algorithm (I_1) makes a decision. Then the status of I_1 will change to waiting until receiving the feedback of its decision. While I_1 instance is waiting to receive the feedback, another instance of non-delayed CE algorithm starts to operate. Clearly, since our delay is equal to four time steps, we need four different instances of non-delayed CE algorithm. As soon as the first feedback arrives, the waiting instance will start to operate. Figure 3 illustrates the time sequence of the Weinberger's algorithm operation with the constant delay of $\tau_0 = 4$.

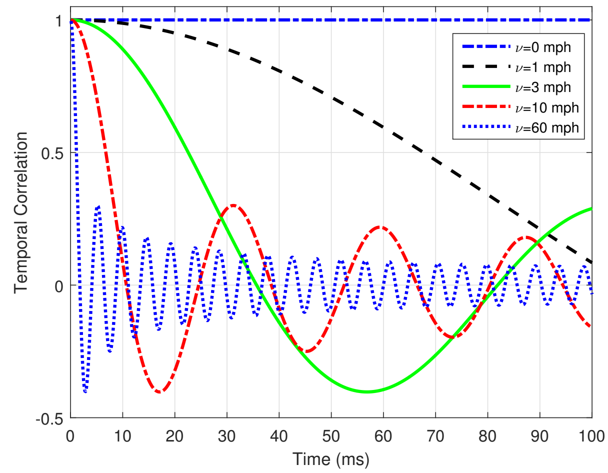


Fig. 2. Temporal correlation vs. delay time, $f_c = 2.4GHz$

In addition to Weinberger's algorithm, to handle the delayed feedback problem in non-delayed CE algorithms, we can formulate CE in the form which ignores the delayed feedback until they arrived. In this form, the CE avoids the idle status in the times that it's waiting to hear back from the receiver. The non-delayed CE algorithm needs to pretend that no decisions are made up to the current time. Then, it will make a decision based on the currently available information. The operation of these CEs will be implemented with two independent threads. While the main Thread is making decisions based on the observed channel conditions at time t, the second thread is waiting to receive feedback from the previously made decisions to update the observation database of the operating CE. We are going to call this type of CEs as Not Waiting CE (NW-CE) algorithms.

To evaluate the performance of the Weinberger and NW-CE algorithms and analyze the effect of delay on a communication system, we use two non-delayed CE algorithms: Gittins strategy and ϵ-Greedy. We also use a 4×4 MIMO system with QPSK, 8PSK, 16, 32, 64, 128 and 256 QAM as a modulation type with eight

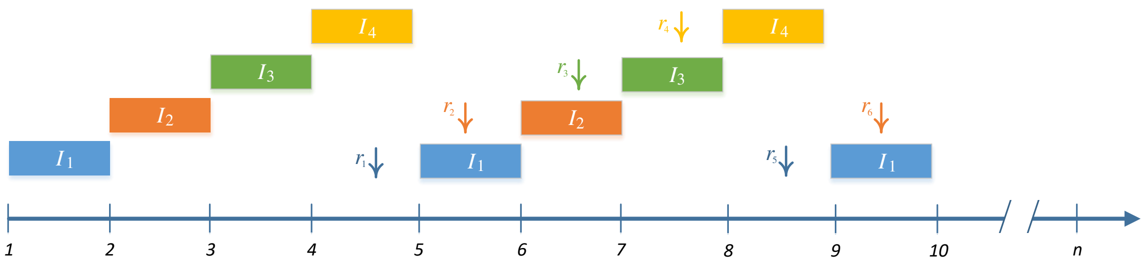


Fig. 3. Time sequence of Weinberger's algorithm operation.

error correction rates: 1, $\frac{7}{8}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{6}$ and $\frac{1}{8}$ and antenna techniques: VBLAST, STBC and MRC. For our channel scenarios, we consider an SNR in the range of 0-50 dB and the log10 of the eigen spread (κ) of the channel matrix in the range of 0-12. The CR also has 12 channels available with different SNRs and bandwidths (either 1.25 or 2.5 MHz).

In the first experiment, to compare the effect of delayed feedback, we consider two scenarios. First, we assume that there is no delay, and that the CE algorithms will receive the feedback immediately. Second, we assume a constant delay based on the LTE protocol to be $\tau_0 = 4$. Figure 4 illustrates the obtained throughput, with their confidence bound by the CE algorithms when there is no delay $\tau_0 = 0$. The results are the mean of 1000 independent experiments. The performance of the CEs represents that after almost 500 time steps, both algorithms will converge to the optimal performance with a tight confidence bound.

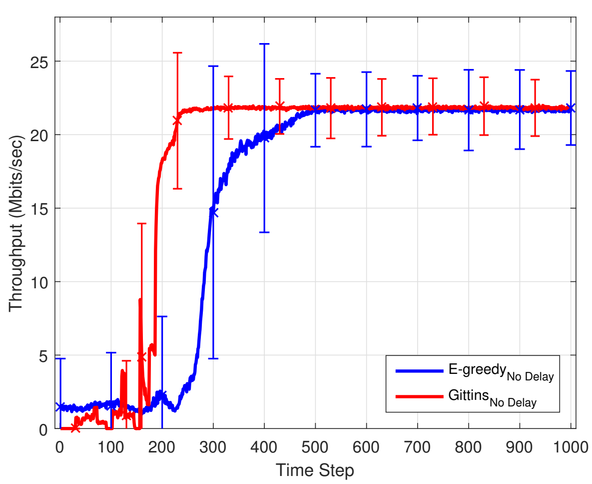


Fig. 4. ϵ-Greedy and Gitting strategy CE algorithms without delay

Figure 5 represents the effect of the constant delay. As we discussed, delay has a multiplicative effect on the regret bound of a CE based on the amount of the delay. The plot shows that none of the CE algorithms are able to find the optimal option in 1000 time steps In addition, their confidence bound illustrates the high level of uncertainty on the obtained performance over 1000 independent experiments.

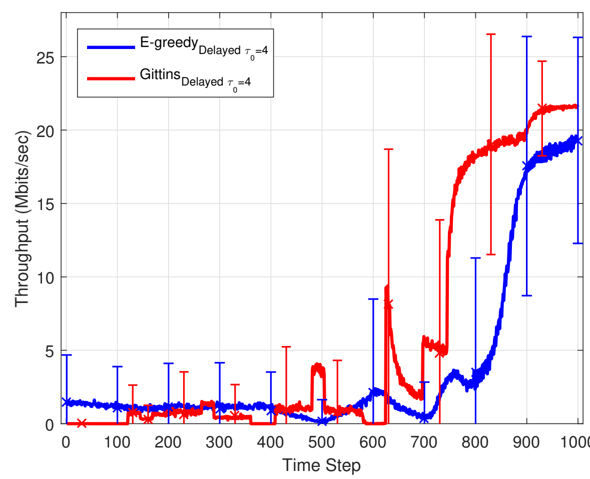


Fig. 5. ϵ-Greedy and Gitting strategy CE algorithms with the constant delay $\tau_0 = 4$

Figure 6 shows the total amount of transferred data with the presence of delay $\tau_0 = 4$ and when the communication system receives the feedback immediately. Clearly, we can see the multiplicative effect of the delay on the total transferred data. This is more clear when we compare the performance of annealing ϵ-greedy [24] algorithm in both cases.

Figure 7 illustrates the results of the NW-CE algorithm in the presence of delay. To generate this result we used the same communication system used for previous experiments and we assumed the constant amount of delay $\tau_0 = 4$. Figure 7(b) shows the effect of the constant delay on the performance of CE algorithms when we use NW-CEs.

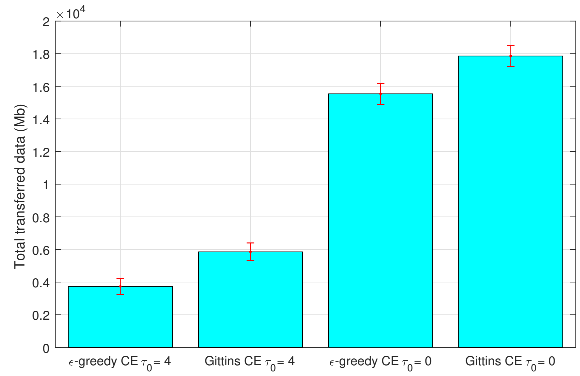
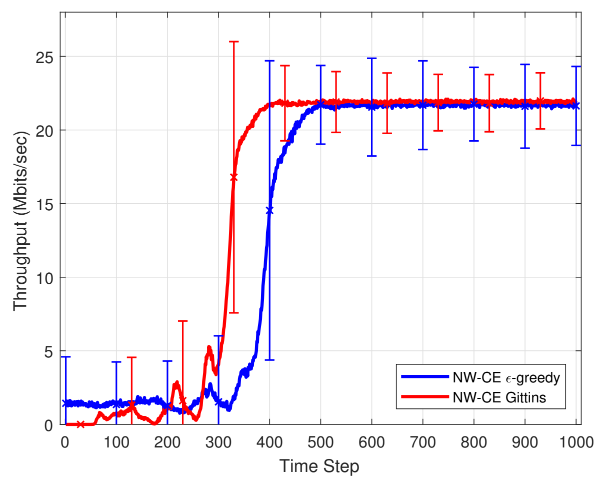
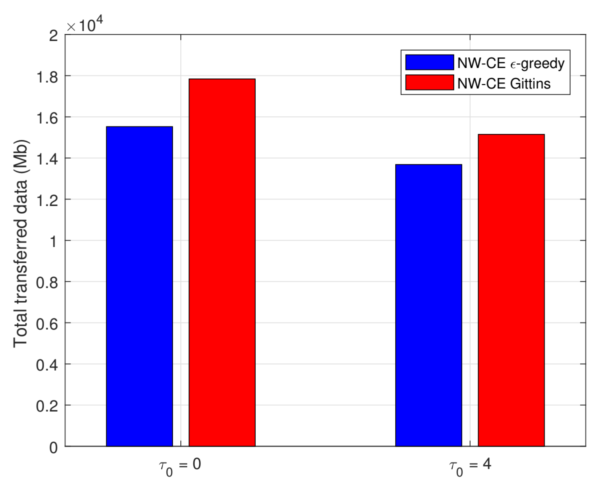


Fig. 6. Total amount of transfered data by using CE algorithms in the presence of delay and without delay



(a)



(b)

Fig. 7. Performance of the NW-CE ϵ-greedy and gittins strategy in the presence of delay with ϵ-greedy and gittins CEs. Part (a) represents the obtained throughput as the objective of NW-CE when $\tau_0 = 4$. (b) shows the total transferred data when NW-CE faces different amount of delays. The figure clears the additive effect of the delay on the regret bound.

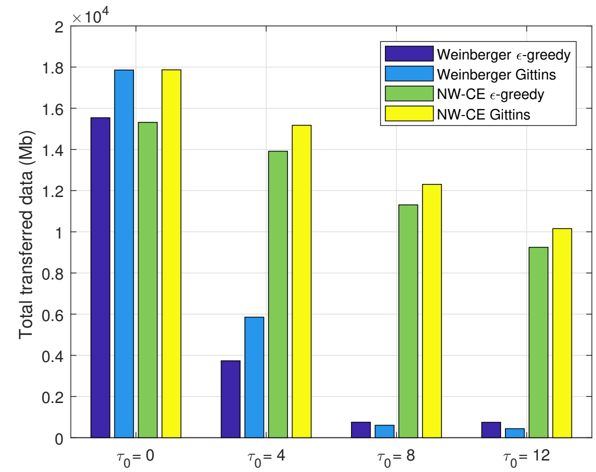


Fig. 8. Comparison between the effects of delay on Weinberger and NW-CE algorithms.

To compare the impacts of the delay on CE algorithms, we considered three different amount of delays and compared the performance of CEs with the non-delayed environment. Figure 8 shows the total data transferred with two CE algorithms: ϵ-greedy and Gittins. We used both Weinberger and NW strategies to handle the delayed feedback with each of CE algorithms. The results indicate that the delay handler strategy plays more important role than the CE algorithm's type. For example, in the Figure 8, the performance of both Gittins and ϵ-greedy CEs exponentially decreased with respect to the amount of delay. However, by using NW strategy, their performance decrease linearly.

IV. Conclusions

In this paper, we studied the effects of delayed feedback on the performance of cognitive radios engines and compared the performance of two different CE algorithms and two different delay handling strategies together. To this end, we first formalized the delayed feedback scenario in wireless communication systems and proposed a stochastic model for the CE's decision-making process in delayed feedback environments. Secondly, we analyzed the effects of delay on CE algorithm's performance. Our results indicate that the delay handling strategies are more effective than the CE algorithms to deal with delayed feedback problem.

Acknowledgements

This project was partially supported by the Broadband Wireless Access and Applications Center (BWAC); NSF Award No. 1265960.

References

[1] H. I. Volos and R. M. Buehrer, "Cognitive Engine Design for Link Adaptation: An Application to Multi-Antenna Systems," *IEEE Transactions on Wireless Communications*, vol. 9, no. 9, pp. 2902–2913, Sept. 2010.

[2] H. I. Volos, C. I. Phelps, and R. M. Buehrer, "Initial Design of a Cognitive Engine for MIMO Systems," in *SDR Forum Technical Conference*, Nov 2007.

[3] ——, "Physical Layer Cognitive Engine for Multi-Antenna Systems," in *Proceedings of the IEEE Military Communications Conference*, Nov. 2008, pp. 1–7.

[4] H. Asadi, H. Volos, M. Marefat, and T. Bose, "Metacognitive radio engine design and standardization," *Selected Areas in Communications, IEEE Journal on*, 2015.

[5] H. Asadi, H. Volos, M. M. Marefat, and T. Bose, "Metacognition and the next generation of cognitive radio engines," *IEEE Communications Magazine*, vol. 54, no. 1, pp. 76–82, January 2016.

[6] ——, "Enhancing robustness and perturbation tolerance of cognitive radio engines with metacognition," *Analog Integrated Circuits and Signal Processing*, vol. 91, no. 2, pp. 173–185, 2017. [Online]. Available: http://dx.doi.org/10.1007/s10470-017-0930-6

[7] H. I. Volos and R. M. Buehrer, "Cognitive Radio Engine Training," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 11, pp. 3878–3889, 2012.

[8] T. W. Rondeau, "Application of Artificial Intelligence to Wireless Communications," Ph.D. dissertation, Virginia Tech, 2007.

[9] A. He, K. K. Bae, T. R. Newman, J. Gaeddert, K. Kim, R. Menon, L. Morales-Tirado, J. J. Neel, Y. Zhao, J. H. Reed, and W. H. Tranter, "A Survey of Artificial Intelligence for Cognitive Radios," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 4, pp. 1578–1592, May 2010.

[10] T. R. Newman, B. A. Barker, A. M. Wyglinski, A. Agah, J. B. Evans, and G. J. Minden, "Cognitive Engine Implementation for Wireless Multicarrier Transceivers," *Wiley Journal on Wireless Communications and Mobile Computing*, vol. 7, no. 9, pp. 1129–1142, 2007.

[11] 3rd Generation Partnership Project, "LTE-Advanced." [Online]. Available: http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced

[12] European Telecommunications Standards Institute, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures," Tech. Rep., 2010.

[13] 3rd Generation Partnership Project, "LTE." [Online]. Available: http://www.3gpp.org/technologies/keywords-acronyms/98-lte

[14] N. J. Nilsson, "Introduction to machine learning: An early draft of a proposed textbook. pages 175-188. http://robotics.stanford.edu/people/nilsson/mlbook.ht ml," 1996.

[15] H. Asadi, H. I. Volos, M. Marefat, and T. Bose, "Learning Characterization Framework and Analysis for a Meta-Cognitive Radio Engine," in *Proceedings of SDRWInnComm 2014 Wireless Innovation Conference on Wireless Communications Technologies and Software Defined Radio*, Mar. 2014, pp. 132–139.

[16] P. Joulani, A. György, and C. Szepesvári, "Online learning under delayed feedback," in *International Conference on Machine Learning (ICML), Atlanta, Georgia,*, June 2013.

[17] S. Guha, K. Munagala, and M. Pal, "Iterated allocations with delayed feedback," *CoRR*, vol. abs/1011.1161, 2010. [Online]. Available: http://arxiv.org/abs/1011.1161

[18] M. J. Weinberger and E. Ordentlich, "On delayed prediction of individual sequences," *IEEE Transactions on Information Theory*, vol. 48, no. 7, pp. 1959–1976, Jul 2002.

[19] ——, "On delayed prediction of individual sequences," *IEEE Trans. Inf. Theor.*, vol. 48, no. 7, pp. 1959–1976, Sep. 2006. [Online]. Available: http://dx.doi.org/10.1109/TIT.2002.1013136

[20] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2001.

[21] J. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2001.

[22] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall Press, 2002.

[23] R. Steele, *Mobile Radio Communications*, 2nd ed. New York, NY, USA: John Wiley & Sons, Inc., 1999.

[24] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*. The MIT Press, March 1998.