A Method for Dynamic Configuration of a Cognitive Radio

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Abstract—

Cognitive radios offer a broad range of opportunities for improving the use and utilization of radio frequency spectrum, they also offer a host of exciting prospects in networking research. This includes the creation of radio networks that can reconfigure their operation based on application requirements, policy updates and environmental conditions. Such reconfiguration requires an understanding of cross-layer interactions within the network protocol stack. It also requires the development of algorithms to determine when such reconfigures should be made, and additionally, the potential impacts of these changes on the radio network. In this article, we describe how cognitive radios can be used to create dynamic wireless networks. Such networks can quickly adapt to the needs of users as well as to changes in the environment. We describe how parameters at the application, physical, data link and network layers interact and how desirable configurations of these parameters can be determined. We then describe a technique that uses these configurations in the creation of an adaptive model for a cognitive radio.

"The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government."

I. INTRODUCTION

The design and implementation of wireless devices is undergoing a substantial transition. While traditionally radio devices had a fixed design and configuration, emerging designs are allowing for much more mutability in both design and configuration. Part of this change has been ushered in by the advent of software defined radio (SDR), a radio with much of its functionality implemented in software [1]. For example, unlike a traditional radio, an SDR might have a modulation scheme that is instantiated in software. A more recent development has been the advent of cognitive radios. These devices are able to reason about their environment and determine when configuration changes are required. Together with the reconfigurable capabilities of SDR, a cognitive radio might dynamically reallocate spectrum or reconfigure itself in response to changes in application demand, operational policy and/or environmental conditions.

Cognitive radios offer a broad range of opportunities for improving the use and utilization of radio frequency spectrum, they also offer a host of opportunities in networking research. This includes the creation of radio networks that can reconfigure their operation based on application requirements (e.g.,

latency or throughput), environmental conditions (e.g., noise floor) and/or operational policies (e.g., commands to vacate a particular frequency band). Such reconfiguration requires an understanding of cross-layer interactions within the network protocol stack. It also requires the development of algorithms to determine when such reconfigures should be made and the possible impacts of these changes on the radio network. In this article, we describe how cognitive radios can be used to create dynamic wireless networks. Such networks can quickly adapt to users needs as well as to environmental changes.

In developing an adaptive cognitive radio network, it is necessary to understand the implications of varying parameters at the physical, data link and network layers. For example, while it might seem intuitive to increase the transmit power of a radio to ensure that it is heard by the intended recipient, this increase could also harm the communication of other nodes in the area. Furthermore, it might not be beneficial to instantiate a forward error correction scheme on a channel with low error rates. Simply put, it is necessary to understand the implications of varying the parameters within a radio. While gains might well be had by increasing power, unintended issues might suggestion alternative configurations. These issues include decisions about when and how to change configurations, how these changes are propagated throughout the CR network, and how much time can be spent computing a change in configuration. While these are all important research questions, this article focuses on the development of a predictive model for CRs.

A number of techniques might be applied when determining the potential interaction of input variables and output responses. In this article, we apply Design of Experiments (DOE), this technique requires the identification of factors (inputs to an experiment with differing values or levels) and responses (outputs of the experiment, observations or measures). A series of experiments is run with permutations of the levels of the factors and the responses are recorded. DOE, through statistical methods, is able to identify the significant factors or combinations of factors that impact the response of interest and produce a model for prediction of the response.

This article is organized as follows. Section II describes the background and related work in cognitive networks and

cross-layer adaptation. Section III provides a simple example illustrating the mechanics of the DOE process. Section IV shows how the most significant CR parameters and their interactions could be determined. Section IV introduces a model for predicting throughput given a CR's configuration. We conclude with a summary of our findings and a presentation of future directions and research opportunities.

II. BACKGROUND

Research in the area of cross-layer optimization for wireless systems has been an area of considerable focus in recent years. Others have also spent a considerable amount time and effort investigating cognitive radios. However, the potential of improving the performance of a wireless system by combining cross layer optimization with cognitive systems is just emerging as a research area.

Much of the work in the area of cross-layer optimization focuses on enhancing throughput, Quality of Service (QoS) and energy consumption [2], [3], [4]. These cross-layer optimizations tend to focus on two layers of the protocol stack with the goal of enhancing a specific performance measure. As such, they do not consider multi-factor variation nor do they consider affects of this variation on inelastic applications, such as Voice over Internet Protocol (VoIP). Kawadia and Kumar present an interesting critique of cross layer design in [5]. They warn that cross layer optimization presents both advantages and dangers. The dangers they discuss include the potential for (1) spaghetti design, (2) proliferation problems and (3) dependency issues. Such cautions (and others that we shall identify) are easily overlooked in the hopes of gaining sometimes marginal performance improvements. Therefore, understanding the significance of the potential improvements is an important step to consider.

Given that the interactions among a set of parameters is determined, the next step is determining the significance of these interactions. In other words, which interactions provide the best response in a given situation. Vadde et al. have applied response surface methodology and DOE techniques to determine the factors that impact the performance of mobile ad hoc networks (MANETs) [6], [7], [8]. Their research considers routing protocols, QoS architectures, media access control (MAC) protocols, mobility models and offered load as input factors and throughput and latency as response factors. Their analysis demonstrates the usefulness of these techniques and shows where certain input factors can outperform others within a MANET.

Haykin provides a thorough overview of cognitive radios and describes the basic capabilities that a "smart" wireless device might offer [9]. Others describe techniques for applying CRs to improving the coordinated use of spectrum [10], [11]. Sahai et al., describes some of the physical layer limits and limitations of cognitive radios, including the difficulties associated with determining whether or not a radio frequency band is occupied [12]. Nishra has implemented a test bed for evaluating the physical and data link layers of such networks [13]. Additionally, Thomas describes the basic concept of a CR

TABLE I
FACTORS AND RESPONSES FOR 802.11 WIRELESS TEST

Factor	Units	Levels	Response
Frame Size	Bits	2048,18432	Latency
Bit Rate	Mbps	1,2	Latency
Transmit Power	mWatts	5,100	Latency

network and provides a case study to illustrate how such a network might operate [14]. It is also worth noting that the standards communities are focusing on cognitive radios. The IEEE 802.22 group is developing a wireless standard for the use of cognitive radios to utilize spectrum in geographically separated and vacant TV bands [15]. Also in the IEEE, the P.1900 workgroup is examining the general issue of spectrum management in next generation radio networks.

III. DESIGN OF EXPERIMENTS

The power of cognitive radio is drawn from its ability to reconfigure in response to a change in the radio frequency environment or a change in the requirements of an application running on the cognitive network. Central to developing any technique for intelligently reconfiguring the cognitive network is a solid understanding of how an individual radio's settings can affect its performance. We sought an approach that would help us determine which settings affect a CR's performance, and settled on a statistical process called Design of Experiments (DOE). DOE is set of tools and methods for determining cause and effect relationships within a system or process [16]. Traditionally, DOE has been used in the process industry to optimize product yield or to maximize production line efficiency. In our case, we use DOE to help determine which configuration of the CR's parameters will have the most positive impact on performance.

DOE is a process that involves a number of steps. The first step is to identify those *factors* (i.e., inputs to an experiment) that you believe will have an affect on the *response* (i.e., output of the experiment). Factors will have different levels or values, for example, an 802.11 wireless card may have the capability to transmit at two different power settings. Specifically, in this simulation the factor, transmit power, has the levels of 32 and 100 mWatts. Whereas the response is a single value that represents a metric, observation, or measure. In our wireless card example, we measure latency, the response, across a noisy link at each of the levels of our factor. Table I shows a set of factors for an experiment wherein we wish to determine which factors, or *interactions* between factors, have the most significant impact on latency. An interaction occurs when a factor at one level does not produce the same response at each level of another factor (i.e., latency is not consistent when power is fixed at 32mW and Bit Rate varies from 1 to 11Mbps). Once the factors, their levels, and the responses are determined you are ready to move on to the next step.

Next we run a set of experiments that iterate through all the combination of factors at each of their levels. Our wireless example requires eight experiments to encompass

TABLE II

RESULTS FROM 802.11 WIRELESS TEST

Run Order	Frame Size	Bit Rate	Transmit Power	Latency
1	2048	1	5	0.01430
2	18432	1	5	0.01257
3	2048	2	5	0.00660
4	18432	2	5	0.00570
5	2048	1	100	0.01453
6	18432	1	100	0.01276
7	2048	2	100	0.00660
8	18432	2	100	0.00580

TABLE III

ANOVA FOR LATENCY

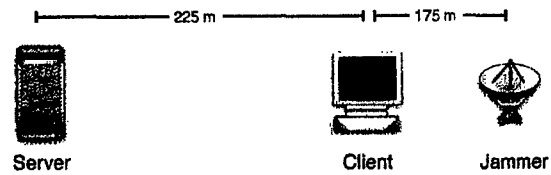| Source	Sum of Squares	df	Mean Square	F Value	P Value Prob<F
Model	1.119E-4	6	1.865E-5	6472	<0.05
A-FrameSize	3.233E-6	1	3.233E-6	1122	<0.05
B-BitRate	1.082E-4	1	1.082E-4	37537	<0.05
C-TransmitPower	2.753E-8	1	2.75E-8	10	0.1992
AB	4.499E-07	1	4.499E-7	156	0.051
AC	9.643E-10	1	9.643E-10	0.335	0.666
BC	1.607E-8	1	1.607E-8	5.573	0.255
Residual	2.883E-9	1	2.883E-9		
Cor Total	1.119E-4	7			
R^2: 0.99					

Fig. 1. Simulation Configuration

Finally, we should look at the model behind the ANOVA. The model is a mathematical equation used to predict the response given a set of inputs. In the general case, the equation is of the form given in (1). Where $\hat{Y}$ is the response and β_0 is the intercept and β_1 is the coefficient for the input factor, X_1. The larger the coefficient the greater the effect on the prediction. The equation for latency in our simple example is given below after reducing the model to only the significant factors (FrameSize, DataRate, and their interaction). See equation (2). We can plug values into this equation and arrive at a predicted latency. To get an estimate of latency for a given configuration of the CR we need only plug values into this equation. For a frame size of 2048 and a bit rate of 2 Mbps (entered as 2000000 bits) we get a value of 0.006585, which is very close to the observed response given in Table II (note, power is not included because our ANOVA did not indicate it as a significant factor). It follows that R^2, a measure of how well a regression line approximates the real data points, is 0.99 (see Table III). Statistically speaking, the model for our simple example provides an almost perfect predictor.

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_{12\ldots n} X_1 X_2 \ldots X_n \quad (1)$$

$$Lat = 0.0226 - 1.644\text{E-}7A - 7.948\text{E-}9B + 5.789\text{E-}14AB \quad (2)$$

IV. DETERMINATION OF SIGNIFICANT FACTORS

In this section, we build upon our wireless 802.11 example by introducing a technique for applying DOE to CRs. The intention is not to necessarily provide the optimal solution; rather we offer an approach for realizing improved performance by matching the needs of the wireless system to changes in the radio environment. We first discuss our simulation environment and then continue with the determination of the significant factors.

A. Experimental Setup and Simulation Environment

In considering the potential complexity of a cognitive network composed of many nodes, we decided to begin by evaluating a simple network. Our scenario consists of a server communicating with a client in the presence of another node (e.g., a noise source or uncooperative node). Figure 1 shows the layout of the client, server, and noise source. We use OPNET Modeler to simulate the effects of changing factor levels on each of the responses. Although OPNET provides an 802.11 wireless module and media access control (MAC) layer, we had to develop our own module to obtain the

all of the possible configurations. Table II shows the set of experiments and the observed latency for each trial. With a simple example such as ours, you may be able to determine the best configuration through simple inspection of the results. However, when there are many factors, levels, and responses optimization by inspection becomes a time consuming, error prone and difficult task.

The next step in our analysis is to make use of statistical methods to help us identify the significant factors or interactions that impact our response, in this case latency. DOE makes use of Analysis Of Variance (ANOVA) to indicate which factors or interactions most impact the response. Rather than provide a primer on the statistics at work in the ANOVA, an interpretation of the results better serves our purposes. Table III is the ANOVA generated for the experimental runs given in Table II. The sum of squares for the model and residual are shown in the first column of the ANOVA table. The next column is the degrees of freedom associated with the sum of squares. Next is the mean square, or the sum of squares divided by the degrees of freedom. The ratio of the mean squares of the model over the mean squares of the residual forms the next column, and is referred to as the *F value*. The F value is compared to the reference distribution for F, in order to determine the probability of observing this result due to error. In this example, we are using the reference distribution for a 95 percent confidence ratio. If you look closely at the table you'll see that Frame Size and Bit Rate and their interaction are the factors that, according to their high F value and their probability for error, are the most significant factors impacting latency (those factors and interactions with a *P Value Prob <* F of 0.1 or less are statistically significant).

TABLE IV
FACTORS AND LEVELS OF EACH

Factor	Levels	Layer
Offered Load	0.5,1.5,5.5 Mbps	Application
Selective Queueing	off/on	Network
Automatic Repeat Request (ARQ)	off/on	MAC
Framesize	2048,9216,18432 bits	MAC
Forward Error Correction	off/on	MAC
Jammer Noise Level	1,4,11 mW	Physical
Bit Rate	1,2,5.5,11 Mbs	Physical
Transmit Power	5,32,100 mW	Physical

TABLE VI
ANOVA FOR THROUGHPUT

Source	Sum of Squares	df	Mean Square	F Value	P Value Prob<F
Model	1.77674E+16	9	1.97415E+15	35505	< 0.0001
A-Load	8.70988E+15	1	8.70988E+15	156647	<0.0001
F-DataRate	3.58178E+15	3	1.19393E+15	21472	<0.0001
H-FEC	2.57725E+13	1	2.57725E+13	463	<0.0001
AF	5.28661E+15	3	1.76220E+15	31693	<0.0001
A^2	1.63309E+14	1	1.63309E+14	2937	<0.0001
R^2: 0.976					

TABLE V
RESPONSES

Response	Units
Bit Loss	Percent
Latency	Seconds
Jitter	Seconds
Throughput	bps

TABLE VII
ANOVA FOR LATENCY

Source	Sum of Squares	df	Mean Square	F Value	P Value Prob<F
Model	159653581	10	15965358	40559	<0.0001
A-Load	52483551	1	52483551	133331	<0.0001
D-ARQ	108251	1	108251	275	<0.0001
F-DataRate	44813234	3	14937744	37948	<0.0001
AD	167242	1	167242	424	<0.0001
AF	61488802	3	20496267	52069	<0.0001
A^2	592501	1	592500	1505	<0.0001
R^2: 0.981					

flexibility we needed. Our newly developed system allows adaptation of the factor levels on a per packet basis.

B. Factors and Responses

As discussed previously, the first step in DOE analysis is selection of the factors that will have a significant impact on the measure or response. Table IV lists the factors that we choose for our experiment and the levels used for each. Some of these factors are a part of the configuration parameters of the device (e.g., FEC and data rate) and others are conditional parameters to which the device is subjected (e.g., noise level or offered load). We selected a set of factors that included multiple layers of the traditional protocol stack, as indicated by the column labeled *Layer*. One might think of the set of factors as a set of dials that one might adjust and the various settings for each factor as the positions on that dial. It is this set of dials that an intelligent process running on a CR would use to configure itself in response to a change in application requirements, policy updates or environmental conditions. DOE requires running 2,592 experiments to cover the permutations of the factors through all of their levels.

There are a host of responses that you could use to evaluate the performance of a cognitive network. We choose those listed in Table V as a representative set of metrics from which to evaluate the performance of a CR.

C. ANOVA for Throughput and Latency

Table VI shows the ANOVA resulting from DOE analysis with respect to throughput. This table is limited to the five factors that contribute most significantly to the response. As you can see load is the primary factor in determining throughput followed by the interaction of load and data rate. An R^2 of 0.976 also indicates that this model closely predicts the response.

Table VII shows the ANOVA resulting from DOE analysis with respect to latency. This table is limited to the six factors that contribute most significantly to the response. As the

results indicate, load again is the primary factor in determining throughput followed by the interaction of load and data rate. An R^2 of 0.981 also indicates that this model closely predicts the response. The following section describes the use of the equations derived from the ANOVA and presents a method for using this equation to configure a CR.

It is worth noting that there are a number of worthwhile questions that are not addressed here. For example, we do not consider how much time a CR can afford to *think* about its next configuration or how a large CR network gets reconfiguration information to all nodes robustly and efficiently.

V. DETERMINATION OF RADIO CONFIGURATION

In this section, we demonstrate how to apply ANOVA-based models for determining a CR configuration in response to changes in policy, environment, or application requirements.

A. The Technique

One might consider two primary approaches when applying this DOE technique to cognitive radio networks. One is to do an a priori DOE analysis to determine an initial configuration of the radio. This technique is used after the radio is brought up in its environment and an initial set of training experiments is run. This data is used in the DOE analysis and the development of the predictive model. The second option is for the predictive model to be used by the system in real-time; thereby allowing the radio to dynamically reconfigure in reaction to changes in the environment, policy, or application needs. However, when the set of factors and levels are large the time required to generate the model prohibits the CR from running the DOE analysis in a reactive manner. With current CPU power it is likely that DOE analysis will remain an offline computation for the next few years.

TABLE VIII
VALUES FOR GENERAL EQUATION (3) FOR THROUGHPUT

Data Rate	FEC	Intercept	β_0	β_1
1 Mbps	off	75086.189	0.570302808	-8.13359E-08
1 Mbps	on	190227.139	0.570302808	-8.13359E-08
2 Mbps	off	259028.107	0.686668263	-8.13359E-08
2 Mbps	on	374169.057	0.686668263	-8.13359E-08
5.5 Mbps	off	-313275.539	1.272905782	-8.13359E-08
5.5 Mbps	on	-198134.589	1.272905782	-8.13359E-08
11 Mbps	off	-490269.329	1.474816703	-8.13359E-08
11 Mbps	on	-375128.379	1.474816703	-8.13359E-08

TABLE IX
VALUES FOR GENERAL EQUATION (4) FOR LATENCY

Data Rate	ARQ	Intercept	β_0	β_1
1 Mbps	off	-41.13091778	6.90218E-05	4.89916E-12
1 Mbps	on	-44.40269207	7.33154E-05	4.89916E-12
2 Mbps	off	-18.39882403	1.34527E-05	4.89916E-12
2 Mbps	on	-21.67059832	1.77463E-05	4.89916E-12
5.5 Mbps	off	21.59021302	-2.91794E-05	4.89916E-12
5.5 Mbps	on	18.31843873	-2.48858E-05	4.89916E-12
11 Mbps	off	25.14024313	-3.29398E-05	4.89916E-12
11 Mbps	on	21.86846884	-2.86462E-05	4.89916E-12

TABLE X
CONFIGURATIONS MEETING 3 MBPS THROUGHPUT GOAL

Bit Rate	FEC	ARQ	Selective Queueing	Frame Size	Transmit Power
11 Mbs	any	any	any	any	any

TABLE XI
CONFIGURATIONS MEETING 3 MBPS THROUPHPUT GOAL WHILE MINIMIZING LATENCY

Bit Rate	FEC	ARQ	Selective Queueing	Frame Size	Transmit Power
11 Mbs	any	off	any	any	any

We present a technique that makes use of the models resulting from our DOE analysis. The process described relies upon the identification of a set of application goals or requirements. Imagine that we have a streaming video application that requires a sustained throughput of around 3 Mbps. In order to reduce our impact on neighboring nodes, we wish to minimize the time that we occupy the channel and our transmit power. In other words, we want our latency and transmit power to be as small as possible while maintaining adequate throughput.

In general, a CR could operate according to the following: (1) The device would perform a set of evaluative probes to characterize its operating environment. (2) It would then take the resulting data and run DOE analysis to derive the relevant models for the responses of interest. In this example, we are interested in throughput and latency. (3) Upon completion of the models, it is possible to generate all potential configurations that meet application and policy goals. (This would be done on a priority basis by eliminating configurations according to primary, secondary, and subsequent goals). In this example, we narrow by throughput first, then by latency, and finally by transmit power. What follows is a simple example illustrating this technique.

$$TP = Intercept + \beta_0 * Load + \beta_1 * Load^2 \qquad (3)$$

$$Lat = Intercept + \beta_0 * Load + \beta_1 * Load^2 \qquad (4)$$

B. Example

In the example, the DOE analysis described in Section III is used. The CR has been set up and has run the initial set of experiments to determine the significant factors for the responses of interest. The ANOVA is completed identifying the significant factors and the underlying model is generated (see prior section). The model for throughput is given in (3). This equation represents a method for predicting throughput given a radio configuration or when applied in reverse the equation can be used to generate all configurations that are capable of providing a given throughput. This is the first step in determining the set of potential configurations that will meet the primary goal of 3 Mbps throughput. In this scenario, there is a streaming video application running on a cognitive network. This application requires a throughput of 3 Mbps. To use the general equation for throughput one needs to apply the proper intercept and coefficients (see Eqn 3). These values are given in Table VIII. For example, a configuration with Data Rate of 5.5 Mbps and FEC set on you would use the values from row 6. When reducing the number of configurations for the desired throughput, the model only identifies those settings using the 11 Mbps data rate. As one might deduce, the 5.5 Mbps data rate is not sufficient to meet the stated goal due to protocol overhead and noise in the environment. When substituting 3,000,000 for load into the equation provided by (3) and Table VIII at the 5.5 Mbps data rate, we get 2,773,419 (FEC off) and 2,888,560 (FEC on) - rates that are not able to meet the required load. The set of potential configurations is now limited to those with the 11 Mbps data rate (in this case there are 72 configurations remaining, see Table X).

The next step involves further reducing this set of configurations in order to minimize latency. When applying the equations in (4) and Table IX the set of configurations is reduced by half, to 36, through elimination of those configurations with Automatic Repeat Request (ARQ) set on. Further reduction of the set of configurations to minimize transmit power, results in those configurations listed in Table XII. The size of this data set could be pruned further if we had not simplified the models for throughput and latency by the top five or six factors. If all the significant factor interactions were included in the model, our technique would identify one *best* configuration - a data rate of 11 Mbps, with FEC set on, ARQ set off, a frame size of 18432 bits, and a transmit power of 5 mW.

VI. CONCLUSION

In this article, we have described how cognitive radios can be used to create dynamic wireless networks. Such networks

TABLE XII
CONFIGURATIONS MEETING 3 MBPS THROUGHPUT GOAL WHILE MINIMIZING LATENCY AND TRANSMIT POWER (DATA RATE = 11 MBS, TRANSMIT POWER = 5 MW AND ARQ = OFF)

#	FEC	Selective Queueing	Frame Size	Predicted Throughput	Predicted Latency
1	off	off	2048	3202158	-29.5869
2	on	off	2048	3317299	-29.5869
3	off	on	2048	3202158	-29.5869
4	on	on	2048	3317299	-29.5869
5	off	off	9216	3202158	-29.5869
6	on	off	9216	3317299	-29.5869
7	off	on	9216	3202158	-29.5869
8	on	on	9216	3317299	-29.5869
9	off	off	18432	3202158	-29.5869
10	on	off	18432	3317299	-29.5869
11	off	on	18432	3202158	-29.5869
12	on	on	18432	3317299	-29.5869

can be used to quickly adapt to the needs of users as well as to changes in the environment. We described methods for determining how parameters at the physical, data link, network and application layers interact and showed how desirable configurations of these parameters can be determined. We also described a technique that can make use of these configurations in the creation of an adaptive model for a cognitive radio.

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