DESIGN OF A LONG RANGE COGNITIVE HF RADIO WITH A TUNED COMPACT ANTENNA

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ABSTRACT

High frequency (HF) communications, ranging from 3 to 30 MHz, are utilized by many radio enthusiasts to conduct transmissions with users across the globe. These communications depend on successfully reflecting signals off the ionosphere. However, numerous factors (i.e. power level, coding, modulation, etc.), combined with the instability of the ionosphere, can make transmissions over this frequency band unreliable. Thus, an HF communication system design is proposed to offer more robust long range HF communications. The system has a cognitive engine that can determine transmission parameters (i.e. coding, modulation, etc.) capable of providing a high throughput and low bit error rate in various environments. The system also has a low-profile helical antenna that, combined with a matching circuit, is capable of receiving signals over different subsets of the HF band. These two components constitute a system capable of effectively transmitting and receiving signals over the HF band.

INTRODUCTION

High Frequency (HF) communications, occurring over the frequency range of 3-30 MHz, has become a popular medium for communications over the past few decades. They enable radio enthusiasts to conduct long-range communications across the globe without the use of a satellite. These communications are conducted using ionospheric reflections to relay the signals across large distances. These reflections can be made with low power and do not require the use of any external equipment (i.e. satellites, beacons, etc.) to transmit signals. Because of this lack of dependence on major communication architectures, in the event of major systematic failure, HF communications would be more reliable than most mainstream communication systems [1]. However, the conditions of the ionosphere are constantly fluctuating and dependent on numerous parameters (i.e. time of day, location, solar flux, etc.), making it a somewhat unreliable medium. In addition, transmis-
sions made over the HF band contain very low data rates. Thus, it is desired to develop a system that can overcome these issues and be capable of making transmissions over the HF band.

This paper proposes a design for such a system with an electrically small helical antenna, matching network, and an embedded intelligent agent known as the cognitive engine. The helical antenna, which is 2 meters in height, is demonstrated employing passive electronically switched matching circuit at discrete frequencies for amateur, maritime, and broadcast applications. In addition, an active broadband matching circuit has been developed to achieve wideband improvement of received signal strength. Furthermore, a wideband unbalanced-to-unbalanced transformer has also been designed, tested, and measured for qualitative analysis in terms of received signal strength, signal-to-noise ratio (SNR), and signal intelligibility. A cognitive engine (CE) is defined as "an intelligent agent which observes the radio environment and chooses the best communication settings that best meet the application’s goal” [2]. In other words, the cognitive engine enables the radio to determine the most optimal method for transmitting in a specific environment. As [3] explains, a radio should be capable of using "a large number of the plethora of current communication methods,...[and] be able to select the method that best meets its objective under the current operating environment." The CE is implemented in software and allows the radio to strategically explore different communication methods and utilize the methods deemed most effective by the algorithms. When a CE algorithm is applied to a radio, the end result is referred to as a cognitive radio (CR). The CR subsequently increases “radio performance and maximizes utilization of the available resources such as power and radio frequency (RF) spectrum” [2].

The following outlines the structure of the paper. First, the background section provides details on the objectives of the helical antenna and matching circuits as well as the CE algorithms that constitute the digital component. The development section provides an explanation regarding the implementation of the CE algorithms and how the current specifications of the helical antenna and matching circuits were obtained. The experimental results section shows verification of the performance of the helical antenna and matching networks in relaying signals from long ranges and the effectiveness of the CE algorithms in determining the best methods for transmitting when trying to maximize a certain parameter (i.e. throughput, power consumption, etc.). The conclusion section provides a summary of the work completed in this project and next steps.

BACKGROUND

A. Cognitive Engine

As stated in the introduction, the objective of the CE is to determine the best configuration for a radio to transmit in any environment. The main complication is that there are numerous parameters to examine; such as, modulation, coding schemes and transmitting power. It is often impractical for the radio to spend large amounts of time determining which combination of these parameters are the most effective for transmitting, especially in situations that require dire urgency [4]. Likewise, it is often not practical to select a single method that may not be as effective as other possible options. Thus, a balance has to be satisfied between experimenting with different parameters for the radio, and utilizing the parameters that have already been determined to be the most
optimal to enable the radio to transmit effectively. This scenario is referred to as "exploration vs. exploitation". Exploration is the experimentation of various options without prior knowledge of each outcome, and exploitation is the usage of the most effective option out of the options already explored [4]. To find this balance, it is best to look at this problem through the perspective of reinforcement learning, algorithms that train a model by rewarding specific actions the model takes. Rewards are defined as "a measure of success" [5], and, in the context of reinforcement learning, are determined by the objective that is desired to be maximized or minimized based on the nature of the objective’s relationship to the communication system (i.e. spectral efficiency, power consumption, etc.). Thus, the objectives of the CE algorithms are to utilize reinforcement learning to find the options that maximize a certain objective, and subsequently providing large rewards, by utilizing different "exploration vs. exploitation" techniques. To set up the general problem solved by the CE algorithms, the following assumptions were made [2]:

1. There are $K$ possible communication methods and each has a potential reward $R_{k}$.
2. Each method $k$ has a potential reward $R_{k}$.
3. The mean $\mu_{k}$ and standard deviation $\sigma_{k}$ are determined from $n$ samples of the reward distribution.
4. Each method has a belief state $\pi_{k}(n)$ that represents what is currently known about the underlying reward distribution at a time step $n$.

Three CE algorithms were implemented in this project. The first is known as the $\epsilon$-Greedy Algorithm, where $\epsilon$ represents the probability that different options are explored. Likewise, $1 - \epsilon$ represents the probability that different options are exploited. The main complication with this algorithm is that $\epsilon$ is fixed, meaning that it will continue randomly exploring/exploiting options at the same rate, which can lead to the algorithm only using sub-optimal configurations or never converging on an appropriate configuration. This observation spurred the development of an annealing version of the $\epsilon$-greedy algorithm, which primarily explores options at the beginning because it is initially unknown if one option is more effective than the others. As knowledge about the performance of different options is acquired over time, $\epsilon$ decreases - reducing the amount of exploration and increasing the amount of exploitation. The update equation for $\epsilon_{d}$ can be found in [2].

The second CE algorithm is known as the Softmax Strategy. Essentially, it incorporates information about the rewards of the present options in its exploration process [5]. This is done by controlling two parameters. The first is $\mu_{k}$, the mean of the reward distribution, to influence the probability associated with selecting a particular method $k$ [2]. In this way, options with a higher mean (i.e. higher reward) will be more likely to be chosen and vice versa. The second parameter is the temperature ($T$). Its usage is similar to how atoms behave in a material exposed to different temperatures. As the temperature increases, atoms engage in random motion, corresponding to random exploration of different options. Conversely, as temperature decreases, atoms tend to move in a slower and more orderly fashion, corresponding to a more structured approach of exploration of different options [5]. In the context of reinforcement learning, high temperatures encourage choosing any option while low temperatures encourage choosing options that give higher rewards. The Softmax expression and update equation for $T$ can be found in [2].
The third algorithm is known as the Gittins Index Strategy. As [2] summarizes, it reduces the K-dimensional problem established at the beginning of this section to "K one-dimensional problems" by using a specific indexing technique. The distribution of $R_k$ that is assumed significantly affects how the Gittins indices are determined. For this application, the Gittins index for the Normal Reward Process (NRP) is utilized, implying that in the event of a successfully received packet, the return will be equal to the rate of the current method chosen. If the packet is not successfully received there is no reward [2]. Because calculating these indices can be a complicated process, a look-up approach is utilized with the indices reported in [6]. To learn more about the Gittins Index Strategy, the reader is encouraged to refer to [3], [4], and [6].

B. Helical Antenna and Matching Circuits

To establish an effective communication link at HF-band wavelengths (i.e. 10-100 meters), large antennas are required; however, this significantly reduces portability. Thus, research has been conducted in developing electrically small antennas that can operate in the HF band. Albeit efforts have be made towards designing small antennas, there are fundamental limitations such as low radiation efficiency, reactive impedance matching, and low bandwidth. Several design approaches such as an electronically switchable broadband loaded antenna for 10.5-30 MHz band [7], a broadband bow-tie shaped HF antenna covering 6-30 MHz band [8], and naval structural antenna systems [9] have been implemented, but the height of the antennas in each application are not less than 15 meters.

DEVELOPMENT

C. Cognitive Engine

For this project, the three CE algorithms discussed in the background section were developed in Python using GNU Radio and LiquidDSP. These two software frameworks are open-source, actively being developed, and contain multiple functions required to perform digital signal processing (DSP) techniques for various software-defined radio (SDR) applications. LiquidDSP enables the implementation of physical layers of various wireless standards (GSM, Wi-Fi, LTE, etc.) and allows for essential physical layer parameters (i.e. preamble length, header, contents, etc.) to be easily set [10]. GNU Radio’s DSP functionality is implemented in various C/C++ blocks, while Python is used to connect these blocks in a very user-friendly way [11].
D. Helical Antenna and Matching Circuits

The vertically-polarized normal-mode helical antenna resonating at 24.5 MHz is designed, fabricated and tested as shown in Figure 1. The proposed antenna is 2 meters long ($H = 2 \text{ m}$), such that it is $\frac{\lambda}{50}$ meters at the lowest frequency. The parameters for the antenna (i.e. helix diameter ($D = 10 \text{ cm}$), number of turns and spacing between the turns ($g = 17 \text{ cm}$) have been optimized to achieve an antenna with low-self resonance along with moderate radiation resistance within the HF band using a commercial full-wave simulation software called ANSYS HFSS.

A passive reconfigurable matching circuit, based on a T-matching network consisting of two inductors and one capacitor, has been proposed for discrete bands. To facilitate instantaneous switching between distinct bands, pin diodes have been used along with independent DC-bias networks as shown in Figure 2. In addition, to overcome the challenges associated with proposed reconfigurable passive matching network, an active broadband non-Foster matching circuit, employing a stable negative capacitor ($\approx -40 \text{ pF}$) based on Linvills negative impedance convertor (NIC) is also designed, fabricated and tested as shown in Figure 2. Stability is an important concern for active non-Foster circuit. A normalized determinant function (NDF) analysis is a theoretical method used to figure out the stability of complex circuits, including multiple-feedback circuits. Hence, an NDF analysis has been carried out, using a circuit simulation software called SPICE, to ensure the stability of the designed matching circuit [12].

The non-Foster matching circuit uses transistors, forcing the design process to require a relatively low noise figure so that the system retains a low SNR. Therefore, transformer matching has also been implemented as it possesses an instantaneous broad bandwidth along with a improved SNR. A broadband 2.5:1 UNUN transformer was designed based on the complete equivalent circuit model of the ferrite transformer, taking into account parasitic reactances, suitable ferrite material, minimum core loss, high power sustainability, galvanic isolation and high load reactance cancellation. A schematic of the fabricated transformer is shown in Figure 2.
EXPERIMENTAL RESULTS

E. Cognitive Engine

The three CE algorithms were simulated using an AWGN channel with multipath, to effectively model an HF environment. The multipath effects were simulated by implementing a two-tap FIR filter in Python. The channel noise was varied to simulate different SNR levels. The objective of these experiments were to maximize throughput through the channel. Table 1 outlines the possible configuration options that could be chosen - consisting of different modulations, inner, and outer codes.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Inner Code</th>
<th>Outer Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>QPSK</td>
<td>Conv-V27 (1/2 rate)</td>
<td>Golay (24,12)</td>
</tr>
<tr>
<td>8-PSK</td>
<td>Conv-V27 (2/3 rate)</td>
<td>ReedSolomon-M8</td>
</tr>
<tr>
<td>16-PSK</td>
<td>Conv-V27 (4/5 rate)</td>
<td>Hamming (7,4)</td>
</tr>
<tr>
<td>DBPSK</td>
<td>Conv-V27 (5/6 rate)</td>
<td>Hamming (12,8)</td>
</tr>
<tr>
<td>DQPSK</td>
<td>Conv-V27 (6/7 rate)</td>
<td>SECDED (22,16)</td>
</tr>
<tr>
<td>8-DPSK</td>
<td>Conv-V27 (7/8 rate)</td>
<td>SECDED (39,32)</td>
</tr>
<tr>
<td>4-ASK</td>
<td></td>
<td>SECDED (72,64)</td>
</tr>
<tr>
<td>16-QAM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32-QAM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64-QAM</td>
<td></td>
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</tr>
</tbody>
</table>

Table 1: Possible Communication Methods

Figure 3: CE throughput (kbps) vs. SNR over AWGN

In the beginning, the CE algorithms have no prior knowledge regarding how effective each of the possible combinations shown in table 1 are. However, as the CE explores these options, it will begin to converge towards the combination of parameters that provide the highest reward with respect to the current objective, which in this experiment was to maximize throughput. For each trial, a packet with a payload of 64 bytes was sent until the 1000th packet was received. Then, the throughput of each packet was determined as shown in equation 1:

\[ C = F \ast \log(M) \ast B \]  

where \( F \) is the combined coding rate of the inner and outer code, \( M \) is the number of symbols in the modulation, and \( B \) is the signal bandwidth which is assumed to be 20 kHz. The results of the experiment are shown in figure 3, with the simulated SNRs ranging from -1 to 20 dB. The throughput of the BPSK modulation option without coding is also included in figure 3 for comparison. Figure 3 indicates that throughput increases linearly with respect to SNR. This trend shows that the CE chooses the best modulation and coding for this HF channel. The configuration that
provided the slowest throughput was achieved using BPSK with a $\frac{1}{2}$ rate code. The configuration that provided the highest throughput was achieved using 32-QAM with a $\frac{3}{4}$ rate code. However, it is expected that this linear trend would not exceed a certain SNR because the channel’s capacity would eventually be reached.

F. Helical Antenna and Matching Circuits

Outdoor near-field test measurements were conducted for a qualitative analysis in terms of received signal power strength. A transmitter source transmitting CW signal power of 16 dBm, situated at a distance of 50 m from the receiving helical antenna with the non-Foster matching circuit, achieved significant improvement in received signal strength. This is in comparison with the case of the passive electronically switchable matching circuit and broadband transformer matching network, as shown in Figure 4.

To evaluate the approximate SNR as a result of using the helical antenna with the three matching circuits, an experiment involving voice transmission over multiple licensed bands was also performed. Single side band (SSB) modulated voice signals were transmitted, with a power of 50W, over a 650 meter line-of-sight distance using a FLEX-6500 software-defined radio (SDR) as a transmitter and the receiver setup shown in figure 5. The receiver setup is largely based on the setup proposed by Ettus Research [13]. It consists of the helical antenna, matching circuit,
Table 2: Receiver: GNU software-defined radio (SNR dB)

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Passive Electronically Switched Matching Circuit</th>
<th>Active Non-Foster Matching Circuit</th>
<th>Passive Transformer Matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.035</td>
<td>15</td>
<td>13</td>
<td>22.5</td>
</tr>
<tr>
<td>7.021</td>
<td>32</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>13.983</td>
<td>67</td>
<td>50</td>
<td>62</td>
</tr>
<tr>
<td>17.615</td>
<td>65</td>
<td>60</td>
<td>65</td>
</tr>
<tr>
<td>29.935</td>
<td>57</td>
<td>58</td>
<td>64</td>
</tr>
</tbody>
</table>

low pass filter, and low noise amplifier, all connected via coax cable. The low noise amplifier is then connected to a USRP N200 with a "BasicRX" daughterboard, which digitizes the signal and transmits it to a PC hosting GNU Radio. A single side band (SSB) flow graph for GNU Radio, also from the Ettus application note [13], is used to process the incoming signal. The flow graph can be adjusted to operate as either an upper or lower side band (i.e. USB or LSB) receiver. It also creates a GUI that allows a user to observe and tune to different frequencies on the spectrum. It was observed that despite the higher received signal strength of the active non-Foster circuit, its SNR performance was not superior to other passive matching circuit prototypes, as shown in Table 2. This is due to the overall increase in the system noise level. It was concluded that passive transformer matching can provide an adequate system performance with minimal transformer loss. Apart from competitive SNR, the ferrite transformer is also advantageous in terms of power handing capacity.

An experiment was also performed to test the receiver setup’s ability to relay long-range communications. Figure 6 shows the approximate locations that could be observed with the setup, where each path is indicative of a different matching circuit used in the receiver. These locations were noted by either hearing the user state it during the transmission, or recording their call sign and reporting the location shown for that callsign on the FCC database. It is worth noting that the figures are not an accurate comparison of the ranges being received by the different matching circuits. The data for this figure was collected at different instances, making it unable to authoritatively assert whether one matching circuit outperformed the others. Such a comparison would also be dependent on the users’ activity (or lack of) at each instance as well. Thus, the figure is only indicative of the general performance of the electrically small helical antenna and the three matching circuits in receiving long-range communications. The blue paths represent the usage of the Passive Broadband 2.5:1 UNUN Transformer. The black paths represent the usage of the active matching circuit. The red paths represent the usage of the reconfigurable matching circuit.
CONCLUSIONS

The objective of this project was to implement a design capable of conducting HF communications. The proposed system consisted of an electrically small helical antenna, matching networks, and a digital component (i.e. CE). The CE was implemented using liquidDSP and GNU Radio, which are commonly used for SDR applications. The design of the helical antenna, resonating at 24.5 MHz, was simulated using ANSYS HFSS. This paper has shown that the components of the long-range HF communications system have been developed effectively. Figure 3 shows that as SNR increases, assuming an AWGN channel, the CE’s performance in choosing optimal communication parameters that maximize throughput also increases (almost linearly). Figure 6 shows that the receiver setup shown in figure 5 is capable of relaying long-range communications over the HF band. One next step that will be pursued is reducing the height of the helical antenna to make it more optimal to carry and set up for a potential user. In addition, more experiments will be planned to verify the performance of the CE over-the-air for long-range HF channels. These experiments will provide further information on the CE’s performance because the effectiveness of the configurations it selects will be tested as the signals experience actual ionospheric reflections. In addition, more advanced CE algorithms will be incorporated to form what is known as a meta-CE [14]. Once this is completed, the CE will be combined to the helical antenna to verify that the whole system can transmit and receive in various HF channels.

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REFERENCES


