DOD/NAVY 15.1 SBIR PHASE I PROPOSAL

Title: Cognitive Radio Architectures for Cyberspace Operations
Firm: Aquerre Technologies LLC
Proposal Number: N151-064-0257
Topic Number: N151-064

1 Identification And Significance Of The Problem Or Opportunity

“As general usage of microelectronic devices increases around the world, multiple competing vendors are attempting to capture a market share through the development of proprietary communications designed protocols for specific applications. Today, there are over 20 standard, wireless commercial protocols, but none of them can satisfy every application requirement. The military can no longer afford a different radio for each network it may wish to utilize or pay a high price to adopt an entirely new protocol. This effort seeks to develop an adaptive, next generation Software Defined Radio (SDR) architecture capable of recognizing many standard protocols and variants, as well as the capability to cross-band the information traffic between any pair on the fly. The demonstration of such a design will minimize obsolescence and logistics costs while maximizing interoperability and adaptive functionality.”–*Topic Description*

Due to the proliferation of networks of wireless devices and the general demand for Radio Frequency (RF) spectrum, adaptive “cognitive radio” methods for dynamic spectrum utilization are used in current and future radio communication systems for opportunistic RF access and co-existence with primary licensed users and other dynamic users. We use the terms ‘dynamic spectrum access’ or ‘spectrum agile radio’ to refer to cognitive radio technologies that sense and adapt their transmitter spectrum based on the RF utilization environment.

In this SBIR Phase I/IA contract we will implement a high-performance rate-adaptive Error Control Code (ECC) in the REDHAWK SDR Development Environment. We will then demonstrate the effectiveness of the implemented ECC with numerical simulation of a spectrum adaptive communications protocol with time-varying power-spectrum utilization and contested radio access. Rate-adaptive ECCs play a natural role in dynamic spectrum access systems due to the dynamic interference profiles posed by multi-user access, in addition to dynamic bandwidth availability.

The commercial advantage of the products delivered in this contract is the advanced function of the underlying PHY layer code, creating new possibilities for dynamically configured radio applications. Further, the ECC implemented in this contract represents a relatively new codec algorithm with high-performance resource utilization. The inventor and author of the initial R&D codec algorithms is the Principal Investigator (P.I.) of this proposal and will be the lead performer on this Phase I-IA contract.

The Phase I software deliverables will include the ECC codec and the associated algorithms implemented as REDHAWK components, and our development tool for analysis, design and construction of the 'software-defined' ECC for a plurality of design (block-length and rate) parameterizations. Phase IA will include the delivery of MAC/PHY simulation tool with detailed performance evaluations of our proprietary Adaptive-Spectrum Access Protocol (ASAP), building upon the products delivered in Phase I. Finally, we will deliver technical documentation of the algorithms and presentation of the quantitative results, including technical demonstration of the simulated system, in this SBIR contract.

1.1 Overview Of The Digital Codec Offered In This Contract

ECCs are a fundamental component of digital communication and data storage systems, and they are needed to compensate for signal distortion due to noise and interference and other signal degradations resulting from the physical transmission media [1].

A primary component of the technology offered in this SBIR contract is the implementation of a high-performance ECC in the REDHAWK SDR Development Environment. The specific ECC subject to this contract, henceforth referred to as the "RC-LDPC-2011" codec, is a Rate-Compatible (RC) Low Density Parity Check (LDPC) ECC, originally introduced at the IEEE Vehicular Technology Conference (VTC) in 2007 [2] and patented in the U.S. in 2011 [3].

The Principal Investigator (P.I.) of the proposing firm is the primary inventor of the RC-LDPC-2011 code design described in [2, 3], and the associated papers and initial Research and Development (R&D) algorithms (including algorithms used to generate the results published in [2]) are available under an open license on our web page: `http://aquerre-technologies.com/software.html`

The RC-LDPC-2011 was developed to be a multi-rate capacity approaching LDPC solution for multiple data block length requirements capable of providing multiple levels of error protection (code-rates) for any given block length. The RC-LDPC-2011 was especially developed for multi-packet codeword protocols (*i.e.* H-ARQ protocol) that adapt to time-varying channel quality conditions by incrementally transmitting the codeword in partial segments, until the receiver is able to decode the codeword data. Hence, by transmitting only as many codeword segments as are needed by the receiver to correct for transmission-channel based signal distortion, the rate-adaptive multi-packet protocol most efficiently utilizes system resources *e.g.* power and bandwidth resources. The ASAP Protocol offered in this contract uses the basic principles of H-ARQ to achieve spectrum adaptability in multi-user/protocol access environments.

The rate-compatible design of the RC-LDPC-2011 makes it ideal for rate-adaptive cognitive radio applications that dynamically adapt their RF spectrum utilization based on user co-existence or opportunistic spectrum access criteria. The REDHAWK ECC codec modules implemented in Phase I will serve as the basis for the development of the Adaptive Spectrum Access Protocol (ASAP) in Phase IA.

This contract includes delivery of the code constructor algorithms, and associated encoder and decoder algorithms, implemented as components of the REDHAWK SDR Development Environment, and separate simulation tools for evaluating system performance with dynamic spectrum access channels and variable system/ECC parameterizations.

The Phase I/IA work plan further includes technical documentation of the associated algorithms, including specification of the rate-adaptive packetized ECC protocol, ASAP, and presentation of the quantitative results obtained from the simulation tool. After demonstrating successful integration into the REDHAWK Environment and simulated performance of the Phase I-IA, we will plan to submit a Phase II proposal, for transitioning the product developed to Government Customer.

Note that, according to the U.S. Patent [3], the commercial-public property-rights to the RC-LDPC-2011 are owned by Alcatel-Lucent USA Inc. (Murray Hill, NJ). Aquerre Technologies LLC is an independent provider of R&D and consulting and contracting services, including any technologies related to [3]. The Government has unrestricted use of any technologies existing or developed during the execution of this Phase I/IA SBIR contract and beyond. Further, Aquerre Technologies reserves the right to seek patent rights for any new technologies invented during the execution of this contract.

1.2 Overview Of Software-Defined Radio

Software Defined Radio (SDR) is refers to radio technologies that utilize software re-configurable hardware. SDR systems capable of reconfiguring their hardware and software are developed for use in multi-radio applications, such as adaptive protocol utilization (multi-protocol support) and adaptive frequency re-use applications.

A design constraint in SDR Engineering is the broad range of hardware requirements needed to support operation at multiple frequencies, data rates and ranges. For example, radio hardware requirements, *i.e.* transmitter power and antenna size, are heavily influenced by the frequency and range of operation. Figure 1 is a plot of the frequency vs. range tradeoff for various data rates (kilo-bits per second), based on the multi-rate link budget analysis detailed in Appendix A. The analysis assumes a line-of-sight channel with a realistic path loss exponent. Similar experiments can be conducted for other power levels, frequencies and channel environments of interest.

The numerical estimates of Figure 1 show the maximum range of reliable communication for the data rates listed and carrier frequency between 500 MHz and 5 GHz, assuming a transmitter power of 20 dBm (0.1 Watt) and signal bandwidth of 5 MHz. For this range of frequencies, the ideal dipole half-wavelength antenna length varies between one foot (500 MHz) and one inch (5 GHz). Hence, a multi-radio device utilizing the whole range would probably require multiple antennas in order to achieve the idealized results depicted in Figure 1. In order to support multiple Physical Layer/Wireless Protocols, the device must further support multiple dynamic software/firmware configurations.

Multi-band SDR technologies for wide-band multi-protocol applications must address a wide range of hardware and software requirements such as antenna size, power, processing complexity and memory constraints. SDR technologies further enable cognitive radio applications, *e.g.* opportunistic users making use of a wide frequency spectrum. These technologies can be used to enable access across a broad spectrum from a consolidated radio

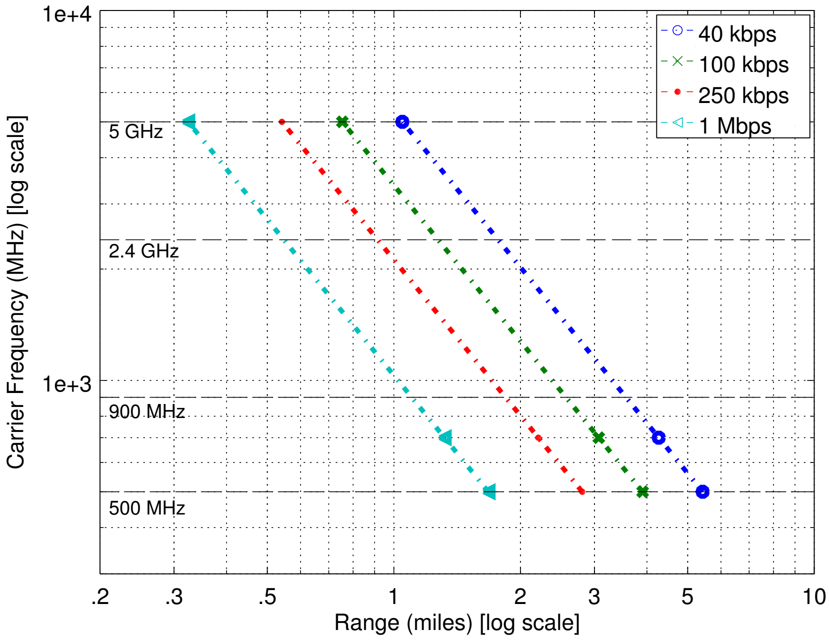

Figure 1: Maximum achievable range for a 20 dBm transmitter and 5MHz channel bandwidth as a function carrier frequency and data rate. The RF transmission model and required receiver SNR for the data-rate are given by the Friis Equation [4] and Shannon Capacity Equation [5], with “real-world” path loss exponent based on results reported in [6] (Appendix A).

device.

Further applications of SDR technology include multi-protocol detection and decoding of primary user radio activity, *e.g.* eavesdropper or wiretap applications, and adaptive RF jammer mitigation such as frequency hopping techniques.

1.3 Overview Of The Spectrum Access Landscape

Radio frequency spectrum utilization in the U.S. is the product of a complex landscape of policy and engineering technology evolution. For example, the DHS lists several hundred Land Mobile Radio (LMR) frequencies that are reserved for disasters or other incidents where radio interoperability is required, ranging from 39.5 MHz to 853 MHz [7]. Interoperability here is mostly intended to mean interoperability of equipment between different agencies/vendors/locales, but it can be more broadly interpreted to include cross-spectrum interoperability.

In this paper we consider a subset of the RF spectrum spanning from 500 MHz to 5 GHz, due to the practical antenna size and signal propagation characteristics in this frequency range. For the range of frequencies considered, the nominal half-wavelength antenna size required for an ideal dipole antenna ranges from one foot (500 MHz) to one inch (5 GHz). Figure 1 shows that a line-of-sight distance between 0.31 to 5.2 miles is theoretically achievable in this frequency range, under the assumptions detailed in Appendix A.

Table 1 contains the summary of a brief online survey, including Wikipedia articles, of radio spectrum access technologies in the range of 500 MHz to 5 GHz. The table lists only some brief details about some of the dominant technologies and hints at the wide diversity of requirements that a truly universal SDR would be required to handle.

In Table 1, we point out a newer protocol, the LTE-Advanced in Unlicensed Spectrum protocol, that makes use of adaptive spectrum methods for co-existence with other unlicensed users. The 5 GHz LTE-Advanced in Unlicensed Spectrum technology uses spectrum adaptive methods to co-exist with WiFi and other users, such as dynamic selection of unused channel and co-channel co-existence with listen-before-talk and adaptive on/off duty cycle [8].

The basic approach to detecting the presence of an RF user in a given frequency and location is to measure the received signal power at the frequency of interest. This is typically performed with detection methods based on non-coherent power (amplitude-squared signal) accumulation at the frequency of interest.

In [11], a basic non-coherent receiver was analyzed for performing rapid estimates of the power spectral density with the Fast Fourier Transform (FFT). Spectrum sensing receivers must be analyzed and calibrated in terms of their detection threshold for determining whether signal is present or noise, and in terms of their time-constant for adjusting to time-varying spectrum utilization and mobility. Additional wireless design factors such as channel multipath (frequency selective fading) and co-channel interference further impact the design and performance of cognitive radio receivers.

Single receiver measurements are further impaired by the "hidden terminal" problem. Hidden terminal problem arises when the transmitter is out of range from the spectrum-sensing receiver, and a null hypothesis is declared, even when other primary users within the sensor's range may be using the channel, *e.g.* hidden broadcast terminal. Hence, distributed spectrum measurement techniques are necessary to fully characterize radio frequency spectrum utilization across a wide geographic area, and to ensure that interfering with primary access users is avoided. Distributed sensing systems further offer the potential for improved detection performance by using diverse location measurements to reduce effective detector noise, as well as the potential for cooperative cross-spectrum routing protocols.

1.4 Application Of The RC-LDPC-2011 To Rate-Adaptive Cognitive Radio Systems

The RC-LDPC-2011 was originally developed as a capacity approaching solution for the Hybrid Automatic Repeat Request (HARQ) protocol of cellular wireless systems. In this contract we generalize the application of the RC-LDPC-2011 to spectrum adaptive cognitive radio systems and develop our own proprietary Adaptive Spectrum Access Protocol (ASAP).

We first review the HARQ protocol and some digital communication fundamentals, as follows. Digital communication and data storage systems utilize ECCs to correct for the imperfect nature of physical communication and storage media. In mobile wireless communication systems, physical channel impairment is complicated by time-varying channel multi-path and co-channel interference.

The Shannon-*capacity* for a given communication channel is defined as the minimum

Carrier	Standard	Notes
5 GHz	WiFi IEEE 802.11a/n	5.15-5.33GHz,5.49-5.84GHz
5 GHz	LTE-Advanced in Unlicensed Spectrum	Co-existence with WiFi [8]
2.4 GHz	WiFi IEEE 802.11b/g/n	802.11n: Max data rate 600 Mbps with 40 MHz channel and 4 MIMO streams
2.4 GHz	IEEE 802.15.4/ZigBee	Cost-effective, low-power wireless technology that can cover large buildings and institutions with mesh networking [9]
2.4 - 2.548 GHz	Bluetooth 4.0	Classic Bluetooth/ Bluetooth High Speed/ Bluetooth Low Energy
2.3, 2.5 and 3.5 GHz	802.16 (WiMAX)	LDPC ECC and multi-hop relay
315, 433, 470, 868, 915, 928, 960 MHz	IEEE 802.15.4g	Sub-GHz ZigBee [9]
700, 750, 800, 850, 1900, 1700, 2100, 2500, 2600 MHz	LTE/LTE-Advanced	Sub-5 ms latency for “small IP packets in optimal conditions”
769-775, 799-805 MHz	700 MHz U.S. Nationwide Interoperability Channels	General Public Safety, EMS, Fire, Law Enforcement, Other Public Service – 6.25 kHz narrow-band Uplink/Downlink channels, combined to get 12.5 kHz and 25 kHz channels. Implemented with LTE Wireless Standard [7, 10]
902-928, 1240-1300, 2300-2310, 2390-2450, 3300-3500 MHz	Amateur Radio	Larger allowable transmitter power/longer range compared to unlicensed spectrum; requires operator license
900 MHz, 1.9 GHz, 2.4 GHz	Cordless Phones	Newer 1.9 GHz used by DECT cordless phone standard

Table 1: A non-comprehensive list of RF access technologies in the 500 MHz to 5 GHz range.

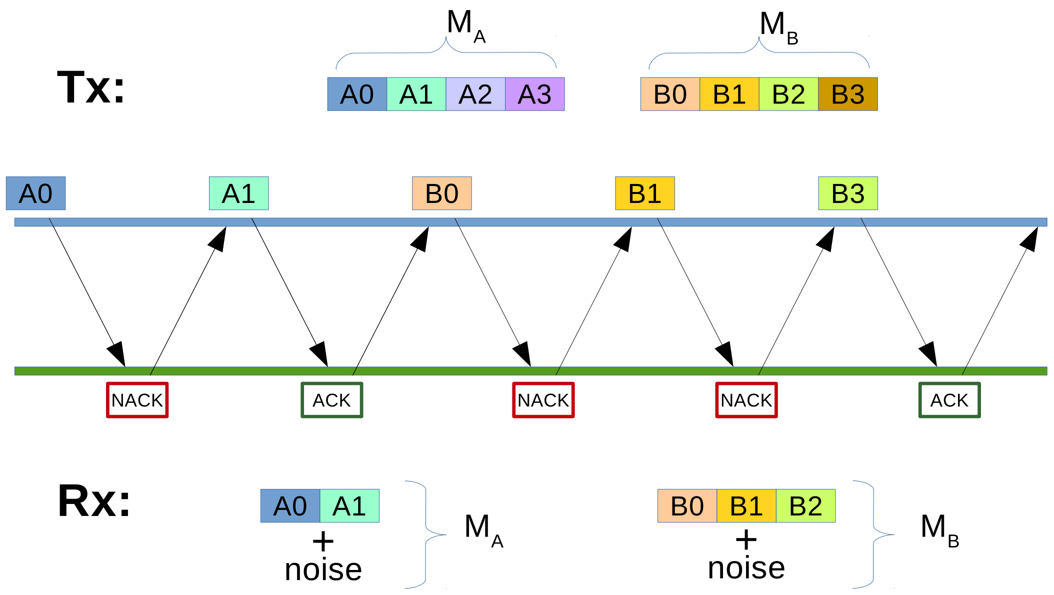

Figure 2: Illustration of a basic H-ARQ protocol with time-varying number of re-transmissions.

Signal-to-Noise Ratio (SNR) required to support reliable communication (*i.e.* with a very small probability of error) at a given data-rate (*e.g.* bits/second). For a fixed power and bandwidth allocation, a capacity approaching ECC uses only as many parity bits as are required by the receiver to overcome anticipated digital errors introduced by the communication-channel. By minimizing the number of transmitted parity bits while still ensuring that the receiver can correctly decode the transmitted message bits with high probability, high-performance codecs efficiently utilize the resource variables, in this case represented by the number of parity bits used to transmit the message bits.

Due to time-varying factors, such as terminal mobility, the capacity of a wireless channel is a random variable that is estimated in order to determine expected feasible resource allocations, *e.g.* power, bandwidth, and rate allocations. The scheduler control program, which allocates system resources across users, may sometimes over-estimate the channel capacity for a given user thereby increasing the probability that the receiver cannot decode at the selected rate and/or resource allocation. In this case, the transmitter will be required to re-send additional information to the receiver in order for the message to be decoded. In the Hybrid-Automatic Repeat Request (H-ARQ) protocol, the re-transmissions consist of additional parity bits effectively yielding a longer received codeword for the same set of message bits.

The definition of a *rate-compatible code* is an ECC that uses multiple sets of parity bits which are combined to form codewords of varying word-length, and therefore varying code-rate, for a fixed set of message bits.

Figure 2 depicts the time-line of a basic H-ARQ protocol. In H-ARQ applications if the receiver cannot decode the transmitted message based on the first received packet, it will indicate this to the transmitter which uses a rate-compatible code to send additional parity information in the form of a new packet so that the receiver can decode the message based on the accumulated received packets for the particular codeword. In Figure 2, the HARQ feedback consists of Acknowledgement (ACK) or Negative Acknowledgement (NACK) indicators, possibly included with other return data to transmitter.

The RC-LDPC-2011 code is an optimized rate-compatible ECC designed to approach capacity at multiple simultaneous code-rates. In particular, the RC-LDPC-2011 is designed to minimize the Signal-to-Noise Ratio (SNR) decoding threshold at multiple simultaneous code-rates, and has demonstrated capacity approaching performance in [2]. Results from [2] are reproduced in Appendix B.

In [2], it was shown that the RC-LDPC-2011 code design simultaneously approaches the AWGN capacity upper bound at multiple rates of operation. It is the first code of its type and demonstrates a wider range of capacity-approaching operational rates compared to other existing rate-compatible codes reported in the research literature.

In H-ARQ applications, it is often more efficient to send additional parity bits than to re-transmit the original codeword. Rate-compatible codes use multiple levels of redundant parity bits to describe a given set of message bits, which make them well suited for H-ARQ applications.

In Phase IA SBIR contract, we build upon the highly efficient RC-LDPC-2011 code design, and products delivered in Phase I, to serve as the basis for the implementation of a proprietary multi-rate Adaptive Spectrum Access Protocol (ASAP). We will further deliver the ASAP MAC/PHY layer protocol using H-ARQ style ACK/NACK feedback in the context of a multi-carrier spectrum adaptive radio simulation environment. We will simulate a scenario in which existing RF users are either cooperative or adversarial. The protocol will be developed to favor cooperative users and to deal with adversarial users as noise/interference or subject to processing by other components.

In this contract, we will leverage our experience in Wireless Standards Development, with the delivery of our proprietary Adaptive Spectrum Access Protocol (ASAP). In particular, the P.I. has experience participating on the LTE/LTE-Advanced and 3GPP2 IEEE Wireless Standards Working Groups, and our contributions, including the RC-LDPC-2011 and related codecs, impacted the development of these standards. In particular, the "TDMA H-ARQ Code for Layer-2 Relay in LTE-Advanced" contribution was introduced in the IEEE 3GPP/LTE Standard Proceedings, with Alcatel-Lucent in 2009 [12].

2 Phase I Technical Objectives

The RC-LDPC-2011 Code will be implemented in the REDHAWK SDR Development Environment. The full code implementation includes the code construction (CC) component, the multi-rate encoder (ENC) component and the multi-rate decoder (DEC) component. The CC component comprises algorithms for generating random instances of the code based on design parameterizations. The generated codes are optimized for multi-rate error protection and are adaptable in terms of block length and supported rates. The ENC and DEC components perform the corresponding encoding and decoding functions for the codes generated by the CC component. The ENC and DEC components must also be adaptable in order to handle a diverse set of rates and block-lengths.

The usable spectrum bandwidth and the available Signal to Interference plus Noise Ratio (SINR) are both possibly time-varying commodities in dynamic spectrum access radio systems. In [2] the performance of the RC-LDPC-2011 with Additive White Gaussian Noise (AWGN) was demonstrated to achieve capacity-approaching decoding thresholds, in terms of Signal-to-Noise Ratio (SNR), for a given bandwidth and set of data-rates. In this contract we will extend upon the original AWGN development results to more complicated dynamic spectrum access channel models, including time-varying SINR channels.

The RC-LDPC-2011 Adaptive Spectrum Access Protocol (ASAP) will make efficient use of available resources by adapting its code-rate with H-ARQ style feedback and effectively using more or fewer redundant (parity) bits based on the receiver feedback. The codeword packets are transmitted incrementally until the receiver acknowledges successful decoding of the message bits, as depicted in Figure 2.

The ASAP cognitive-radio protocol delivered in this contract will be based on the RC-LDPC-2011 codec [2, 3] and associated REDHAWK components delivered in Phase I and Phase IA. The Principle Investigator has experience contributing to the LTE-Advanced standard working group on the topic of relay PHY layer specification and authored the contribution pertaining to the cooperative relay H-ARQ protocol [12].

The technical objectives further include the development of an adaptive spectrum, adaptive-rate simulation tool based upon the RC-LDPC-2011 REDHAWK code components and the ASAP specification. The MAC/PHY layer simulation-tool will use H-ARQ style feedback to dynamically adapt the transmission signal to time varying spectrum utilization patterns. A technical demonstration of the simulated system will be provided with, for example, a simulation of the transmission of video signals with adaptive resolution based on opportunistic dynamic spectrum access.

The codec algorithms will be implemented as REDHAWK components. The other simulation tools, *i.e.* the codec development simulation tool and the adaptive protocol simulation tool, will be implemented using REDHAWK, C/C++ and GNU Octave.

The work plan and methods for achieving these objectives are detailed in the following sections.

3 Phase I Statement Of Work

Aquerre Technologies is committed to meeting all DOD/NAVY SBIR reporting and documentation schedules and requirements. Details of our Phase I/IA work plan, including list of deliverables, description of work plan and schedule of events, are contained in the following sections. The total requested amount for Phase I is $79,974 and Phase IA is $69,988.

3.1 Phase I Deliverables

1. REDHAWK ECC components comprised of the RC-LDPC-2011 multi-constructor (CC), encoder (ENC) and decoder (DEC) algorithms.

2. Phase I ECC, including adaptive constructor (CC), testing and evaluation tool .

3. Phase I Specification of the Adaptive Spectrum Access Protocol (ASAP), based on the the RC-LDPC-2011 and components.

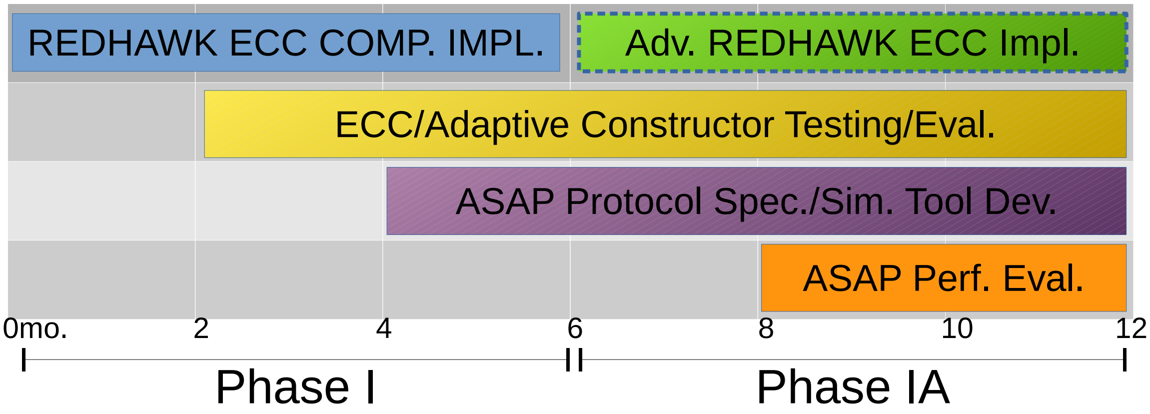

Figure 3: Proposed schedule for the Phase I/IA contract. Each block represents a work-thread, where the time allocation across threads may vary.

4. Detailed technical specification of all Phase I algorithms.
5. Phase I midterm (3 mo.) report and Phase I report (6 mo.).

3.2 Phase IA Deliverables

1. Phase IA release of the REDHAWK ECC components including any updates resulting from the concurrent Phase IA development efforts.
2. Phase IA release of the ECC testing and evaluation tool.
3. Phase IA simulation tool for evaluating the ASAP protocol in cognitive radio applications, including opportunistic access systems
4. Detailed technical specification of all Phase IA algorithms.
5. Phase IA midterm report (9 mo.) and Phase IA final report (12 mo.)

Aquerre Technologies further commits to delivering a Phase II proposal for the follow-on Phase II contract of this SBIR program.

3.3 Schedule Of Major Events

Figure 3 depicts a time-line of the multi-threaded work plan scheduled for Phase I and IA of this contract. Details of the work plan are discussed below.

3.3.1 Phase I REDHAWK Implementation Of The RC-LDPC-2011 ECC

Implementation of the RC-LDPC-2011 codec (ENC/DEC) and associated code construction algorithms (CC) in REDHAWK represents a primary component of the Phase I work plan. The P.I. is the author of the R&D development algorithms associated with [2, 3] and will play a fundamental role in implementing the new components in the REDHAWK SDR Development Environment based on the existing R&D code-base.

3.3.2 Phase I-IA ECC/Adaptive Constructor Testing/Evaluation

At two months, the development work in the REDHAWK suite is expected to yield a basic working codec and the ECC/Adaptive Constructor Testing/Evaluation work thread will begin. The objective of this effort is to provide ongoing development feedback through testing and evaluation of the REDHAWK codec components by means of a separate codec testing and simulation tool. For example, the response to noise and interference will be be modeled with the simulation tool, in addition to the development of time-varying channel models. This effort will require additional software development in the form of algorithms for design, testing and interfacing with the codec components, including algorithms for quantitative evaluation, *e.g.* 'Monte Carlo' numerical methods. These testing and evaluation modules will serve as a primary source of development feedback for the Phase I and IA REDHAWK ECC Implementation and Advanced ECC Implementation work threads.

3.3.3 Phase I-IA ASAP Protocol Specification And Simulation Development Tool

The ASAP Protocol Specification and Simulation Development Tool work thread will begin at four months. By the completion of Phase I (six months) we will have a detailed specification of the ASAP protocol for cognitive radio applications. ASAP will build upon the RC-LDPC-2011 codec and associated components, utilizing the multi-rate, multi-block-size constructor for rate-adaptive communication in dynamic spectrum access systems.

Starting in Phase IA will be the development the ASAP Simulation Tool, with MAC and PHY layer components. The objective of ASAP Simulation Tool will be to evaluate the adaptive spectrum protocol (ASAP) specified in Phase I in the context of a contested dynamic spectrum access environment. The tool will simulate the dynamic spectrum environment and will be used to provide feedback for the design of SDR/cognitive radio systems base on the REDHAWK ECC products delivered in this contract. The Phase IA work thread for ASAP Simulation Tool development will further provide feedback for the Phase IA iteration of the ASAP Specification.

3.3.4 Phase IA Advanced REDHAWK ECC Implementation

The Phase IA Advanced REDHAWK ECC Implementation work thread is focused on integrating ongoing testing and evaluation feedback into the REDHAWK component algorithms to provide further advancements in support of the Phase IA release of the REDHAWK ECC product delivered in this contract. Further driven by the concurrent ASAP work thread and development feedback cycle, new and expanded functions to the REDHAWK ECC components (CC/ENC/DEC) will be added in the Phase IA release.

3.3.5 Phase IA ASAP Performance Evaluation Studies With Phase IA Simulation Tool

Performance evaluations of the ASAP adaptive cognitive radio protocol work thread will commence at 8 months culminating with the Phase IA final quantitative reports at 12 months.

Iterative simulation studies will throughout this work thread will be used to generate feedback for the concurrent Simulation Tool Development and Advanced Codec Development work threads.

3.4 Phase II and Beyond

Aquerre Technologies seeks to deliver custom solutions based on specific customer needs and we will work closely with the sponsor, throughout all phases of the program, to ensure that our commercialization plan is tailored for successful integration into customer systems.

Throughout this SBIR we will actively participate in commercialization assistance programs such as the Navy Transition Assistance Program (TAP) (Phase II) and the DOD Commercialization Readiness Program (CRP) (Phase II.5).

4 Related Work

The P.I. has related research expertise in cellular wireless physical layer technologies, including non-coherent Quadrature Amplitude Modulation (QAM) techniques [13] and MIMO techniques [14], with specific emphasis on approaching Shannon-theoretic limits with practically realizable systems.

The P.I. has post-doctoral research experience on methods for cognitive radio applications, with the University of California, Santa Barbara [11], and he further served as a consultant for Toyon Research Corp. in regards to spectrum sensing for satellite link re-use cognitive radio applications [15].

Related work on HARQ Protocols comes from Bell Labs Research and collaborators in [16], specifically, the authors investigated the use of incremental redundancy based on puncturing in HARQ protocols. Also, the P.I. was the author of the cooperative relay HARQ protocol with Alcatel-Lucent, introduced in the LTE-Advanced Standard [12].

5 Relationship With Future Research Or Research And Development

The anticipated results of the proposed Phase I-IA work plan are the development of pre-prototype components for the REDHAWK SDR Environment. The REDHAWK Framework is used for development, deployment and management of SDR applications. Upon successful completion of the Phase I-IA contract, we will be in prime position to leverage our advanced R&D and proprietary algorithms in the Phase II transition to commercial product. This SBIR program will strengthen the position of Aquerre Technologies as a leader in cognitive radio research and development services for Government and other commercial customers, throughout the SBIR program and beyond.

As indicated in the topic description, this SBIR is ITAR restricted and the Phase II work program of this SBIR contract may require security clearance(s). All personnel performing work on this contract are expected to be U.S. citizens. The P.I. does not currently possess a security clearance. In the event that such clearances are necessary to conduct Phase II

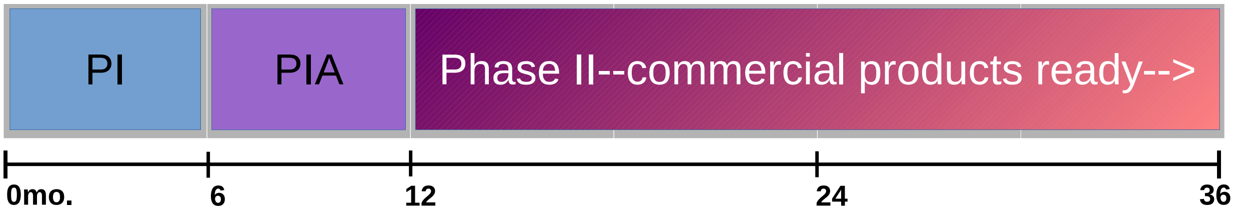

Figure 4: Time-line of the Phase I-IA-II program with commercial readiness for Government customer by the end of Phase II.

development work, we will work closely with the sponsor to ensure timely completion of the applicable processes.

6 Commercialization Strategy

The primary application of the offered technology is for evolutionary and next generation DOD/NAVY cognitive radio systems. The estimated market size is large due to the diversity and widespread use of networks of wireless devices and the need for common access platforms.

Aquerre Technologies seeks to be a primary vendor of advanced signal processing algorithms and simulation tools for Government SDR/cognitive radio systems. Our custom solutions will be specifically developed to satisfy ongoing DOD/NAVY strategic needs.

A secondary commercialization objective of this SBIR program will be to seek patent rights for the technologies invented during the execution of the contracts, for potential use in open commercial markets.

For Government SDR systems based on the REDHAWK framework, there is not a huge cost associated with bringing new algorithms and software components to market due to the distributed/componentized development and implementation framework. Hence, we foresee the ability to rapidly commercialize technology for Government customers within the time frame of the Phase II SBIR contract. If it is determined that there are technical hurdles in the associated hardware capabilities of the SDR/cognitive radio system, we will address these in the Phase II proposal. We will further address the minimum requirements for implementing the offered product components. The anticipated time-line for commercialization readiness is depicted in Figure 4.

Aquerre Technologies acknowledges the competitive vendor market for serving U.S. Government needs, and in this SBIR contract we emphasize our specialized expertise and the advanced performance of the proprietary technology offered. We will seek to work closely with the sponsor to make sure our products anticipate ongoing customer strategic needs. Finally, we will actively participate in DOD/NAVY commercialization assistance programs.

7 Key Personnel

7.1 Noah B. Jacobsen, P.I.

Dr. Jacobsen will be the lead performer on this SBIR Phase I-IA contract. He is an expert in field of digital and wireless communication systems and has served as a consultant on cognitive radio applications (Toyon Research Corp.). He is scheduled for 1520 hours over the course of the 12 month contract. His CV is copied below:

Education

- Ph.D., 2005, Electrical and Computer Engineering, University of California, Santa Barbara.
  - Specialization: Communication, Control and Signal Processing.
- M.S., 2002, Electrical and Computer Engineering, University of California, Santa Barbara.
- B.S., 2000, Electrical Engineering, Cornell University.

Professional Experience

- Aquerre Technologies LLC: Founder, CEO, Principal Scientist (May 2013 – present).
  - Research and development contracting and consulting services.
- Dex One: Sr. Operations Research Scientist (Sept. 2012 – March 2013).
  - Advertising technology predictive analytics.
- Columbia University: Adjunct Professor (Spring Semester 2012).
  - Linear Systems Theory, Dept. of Electrical Engineering.
- Alcatel-Lucent, Bell Labs: R&D Engineer (July 2006 – Oct. 2011).
  - Error control codes, cooperative relay codes, physical layer communications research, standardization, and development. Includes experience transitioning algorithms to product teams.
- Polytechnic Institute of New York University: Adjunct Professor (Fall Semester 2010).
  - Probability Theory, Dept. of Electrical and Computer Engineering.
- University of California, Santa Barbara: Post-Doctoral Researcher (Sept. 2005 – June 2006).
  - Cognitive radio networks, communication theory.
- Toyon Research Corporation: Consultant (Mar. 2006 – June 2006).
  - Cognitive radio networks, communication theory.

Conferences

- Attendee, 2014 National SBIR/STTR Conference and Short Course “How To Develop An Acceptable Accounting System”, Washington, DC, Jun. 16–18, 2014.

Certifications

- California Basic Educational Skills Test (CBEST) Completed, December 2013.

Patents

- N. Jacobsen and R. Soni, "Method and system for encoding data using rate-compatible irregular LDPC codes based on edge growth and parity splitting", U.S. Patent No. 7,966,548, June 2007.

Book Chapters

- G. Barriac, N.B. Jacobsen and U. Madhow. "Chapter 5: The role of feedback, CSI and coherence in MIMO systems," in: Space-time wireless systems: From array processing to MIMO communications, H. Bölcskei, D. Gesbert, C. B. Papadias and A.-J. van der Veen (Ed.), Cambridge University Press, 2006.

Achievements

- Session Chair, "Wireless Networks and Communications," 43rd Conference on Information Sciences and Systems (CISS), March 18-20, 2009.
- 3GPP2 Ultra Mobile Broadband (UMB) Air Interface Specification: Recognition of Contribution, LDPC Ad Hoc Group, 2007.
- National Science Foundation (NSF) and Japan Society for the Promotion of Science (JSPS) East Asia Summer Institutes Fellowship, Yokohama National University, Japan, 2003.
- Microelectronics Innovation and Computer Research Opportunities Scholarship, University of California, Santa Barbara, 2000–2001.
- Theodore C. Ohart Scholarship in Engineering, Cornell University, 1999–2000.
- Cornell University College of Engineering Cooperative Education Program, with Floyd R. Newman Laboratory of Nuclear Studies, Cornell University, 1998–1999.
- Cornell University Dean of Students Service Award: "Selections Director," Cornell Concert Commission, 1998 and 1999.

Software and Programming Experience

- GNU Linux (expert), Debian, C/C++, Bash Shell Scripting, OpenOffice (Writer/Calc/Impress), Octave (similar to MatLab), Java, SQL, BASIC, HTML, Emacs, Vi, Gimp, Ardour, Audacity, Mozilla
- REDHAWK Development Environment Build/Install from source on Debian Linux

7.2 R&D Engineer

Upon award of contract, we will hire an R&D engineer (part-time) to work specifically on this SBIR contract. We will hire a diverse applicant with both relevant software algorithms experience as well as hardware experience. The P.I. has numerous academic contacts that could potentially be leveraged for recruiting talent, *e.g.* University of California, Santa Barbara. In particular, we will seek to hire a U.S. citizen for the position associated with this contract.

The R&D Engineer will be committed to this SBIR program on a part-time basis for a total of 800 hours over the course of the Phase I and IA contract. (Note that the P.I. will be committed at 1520 hours.) The role of the R&D Engineer will be to assist the P.I. in execution of the contract primarily through software development, testing and simulation, and technical documentation.

8 Foreign Citizens

This topic is marked as ITAR restricted. We anticipate that all personnel performing work on this project will be U.S. citizens.

9 Facilities/Equipment

The primary business office of Aquerre Technologies LLC is currently located at 1445 Colby Ave #3, Los Angeles, CA 90025. All facilities, equipment, and data management supporting the Phase I and IA segments of this SBIR program will be based out of our primary office. We have a separate initiative to re-locate/upgrade our facility situation and will apprise the sponsor regarding any developments should there be any. We will work closely with the sponsor to ensure that our facilities and equipment are adequate for program requirements throughout all phases of the SBIR program.

10 Subcontractors/Consultants

Neither sub-contractors nor consultants are included in the Phase I/I.A proposal.

11 Prior, Current Or Pending Support Of Similar Proposals Or Awards

Aquerre Technologies LLC has no prior, current, or pending support for the work proposed for this SBIR program.

12 Discretionary Technical Assistance

The use of Discretionary Technical Assistance (DTA) is not included in this proposal.

Appendices

Carrier	Bandwidth	Data Rate	Tx. Power	Range
900 MHz	5 MHz	40 kbps	24 dBm	∼ 2 mi.
2.4 GHz	5 MHz	250 kbps	20 dBm	1 mi.

Table 2: Data points inferred from [6], based on outdoor measurements with 802.15.4 across an open lake.

A Multi-Rate Link Budget Analysis

We estimate the maximum range (distance) as a function of carrier frequency and data-rate. According to the Friis Equation of antenna transmission theory, the received signal power is a quadratic function of the carrier wavelength [4]. We assume a channel bandwidth (BW) of 5 MHz and various possible data-rates, denoted C. The receiver thermal noise power at room temperature for 5MHz bandwidth is given by (*e.g.* [17]):

$$\begin{aligned} N_r &= k_B \times T \times BW && (1)\\ &= (1.38 \times 10^{-23}\ \mathrm{J/K}) \times (290\ \mathrm{K}) \times (5 \times 10^{6}\ \mathrm{Hz}) && (2)\\ &= 2.0 \times 10^{-14}\ \mathrm{W} = -107\ \mathrm{dBm} && (3)\end{aligned}$$

Application of Shannon's Capacity Equation

$$C = BW \times \log_2\left(1 + \frac{P_r}{N_r}\right) \tag{4}$$

yields the theoretical minimum received power P_r required to communicate at rate C bits per second:

$$P_r(C) = N_r\left(2^{C/BW} - 1\right). \tag{5}$$

We then apply the Friis Equation with variable path loss exponent p [18], to determine the received signal power at range R, for transmitter power P_t and carrier-wavelength λ:

$$P_r = P_t \times \frac{G_{link}\lambda^2}{(4\pi)^2 R^p}, \tag{6}$$

where we have used the factor $G_{link} = G_t G_r$ to model the antenna gain factors and any additional non-idealities such non-ideal receiver noise. The parameters p and G_{link} were chosen to be consistent with the measurements reported in [6], for an 802.15.4 system at 900 MHz and 2.4 GHz and an outdoor lake channel. The path loss parameter is chosen as $p = 2.8$ to be consistent with the data provided in Table 2. The G_{link} factor assumed is 0 dB and the transmitter power P_t is assumed to be 20 dBm.

Using the above assumptions, the maximum achievable range for the data rate C and carrier frequency f is given by:

$$R(f;C) = \left(\frac{P_t G_{link} c^2}{P_r(C)(4\pi)^2 f^2}\right)^{1/p} \tag{7}$$

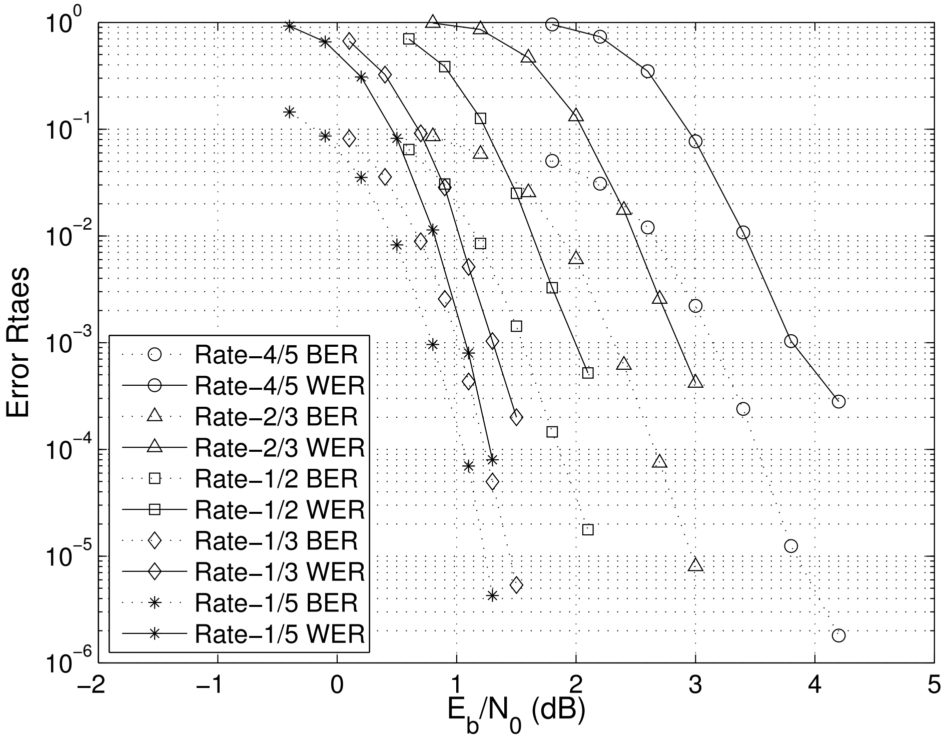

Figure 5: Codeword Error Rate (WER) and Bit Error Rate (BER) Performance of rate-compatible irregular LDPC codes, k = 600 (number of message bits).

where c denotes the speed of light and $P_r(C)$ is defined in Equation (5). Figure 1 plots the estimated range data for the 500 MHz to 5 GHz frequency-band, for the data rates C=40, 100, 250, and 1000 kbps. Because we have used the Shannon-capacity formula to estimate the cut-off distance for reliable communication, the range estimates given by this analysis represent an upper bound on the distances achievable for the given carrier frequency and data rate, approachable only in idealized cases and requiring the use of a capacity approaching ECC.

B Published Results On The RC-LDPC-2011

Figures 5 and 6 are reproduced from [2]. Figure 5 shows the simulated error rate performance of the RC-LDPC-2011 assuming the codewords are transmitted using Binary Phase Shift Keying (BPSK) over an Additive White Gaussian Noise (AWGN) channel with the associated Signal-to-Noise Ratio (SNR).

A BER rate of 10^{-4} is used to estimate the decoding threshold (SNR) required for the receiver to decode at the given block length and code rate in Figure 5. The decoding thresholds are then compared to the Shannon-capacity in Figure 6. The comparison to capacity shows that as the block length of the code increases, the RC-LDPC-2011 code uniformly approaches the capacity (in SNR) at its multiple supported rates.

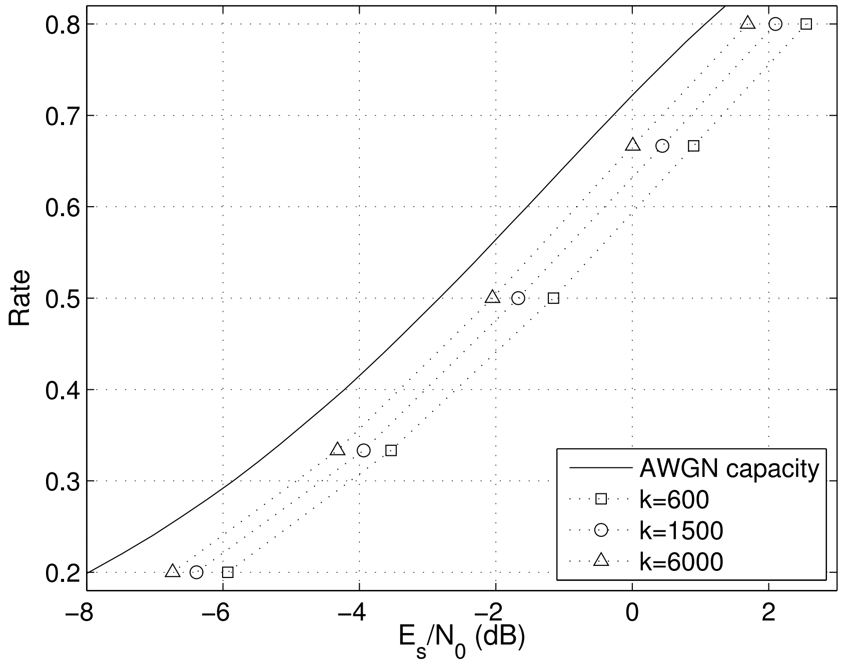

Figure 6: Gap to capacity of the rate compatible codes. Each dashed line represents a family of codes of various code-rates (1/5, 1/3, 1/2, 2/3, 4/5) for a different message block size, k bits.

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