



Technical Report

**STI: Flexible Wireless Systems for Rapid Network  
Evolution—Final Report**

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# Flexible Wireless Systems for Rapid Network Evolution

## Final Report

### 1 Introduction

Ultra-wideband (UWB) systems portend to offer multiple communications advantages. However, the conventional approach to UWB systems is to emit a short, possibly shaped, pulse at determined intervals. The effect is not unlike your car engine firing a spark plug at determined intervals. Advocates contend that by shaping the pulse and adjusting the interval between pulses, a robust, short-ranged communications system can be achieved. However, traditional UWB systems have only two degrees of freedom, pulse shape and pulse interval. This limits their ability to avoid interfering or critical (e.g. GPS) channels and comply with United States and foreign laws regarding spectrum management.

We investigated solutions to these issues within the UWB approach, by developing, implementing, and demonstrating an ultra-wideband communications system based on hundreds of individual carrier channels. We initially called our approach Hyper-Orthogonal Frequency Division Multiplexing, or H-OFDM. But, during the course of the project, we switched to the more descriptive Non-Contiguous OFDM or NC-OFDM. We will use NC-OFDM in this report. Such systems will allow the rapid deployment of new wireless Internet services by providing a platform that is flexible with respect to the ambient spectrum regulations and conditions. NC-OFDM permits the mining of the existing spectrum to obtain bandwidth to support new networking services. The NC-OFDM system has the following attributes:

1. The radio frequency (RF) environment can be sensed and the system can adapt to the local environment.
2. The NC-OFDM system can adjust to local (foreign) regulations regarding RF emissions.
3. The NC-OFDM system can adjust to propagation conditions, using lower frequencies to penetrate foliage and/or reach longer distances or use higher frequencies to limit range and support covert operations.

We proposed to implement a wideband, flexible software defined radio during the first two years of the project and implement wideband protocols in the third year. In practice, it took longer to implement, that is design, procure parts, build, test, and develop a software infrastructure, the software defined radio than we anticipated. We accomplished the following:

1. Designed and implemented a comprehensive OFDM simulator in MatLab to evaluate design tradeoffs (ITTC-FY2008-31620-04).
2. Analyzed multiple approaches to NC-OFDM systems (ITTC-FY2008-31620-05).
3. Built a wideband, flexible, software defined radio, called the KU Agile Radio, for experimentation (ITTC-FY2008-31620-02, ITTC-FY2008-31620-03, and ITTC-FY2008-31620-07).

4. Implemented an OFDM waveform on the KUAR based on a subset of IEEE 802.16 (ITTC-FY2008-31620-06).
5. Presented our results at conferences, in journals, and successfully demonstrated the KUAR at IEEE DySPAN 2007 in Dublin, Ireland.

### 1.1 Rationale for a NC-OFDM Based Flexible Wireless System

We are concerned that traditional approaches to UWB systems ignore regulations within the United States and foreign countries.

Within the United States, the radio frequency spectrum is managed by the National Telecommunications and Information Administration (NTIA), within the Department of Commerce, and the Federal Communications Commission (FCC). NTIA allocates spectrum to government departments and the FCC manages spectrum for the commercial sector. The NTIA and FCC coordinate spectrum allocation within the United States. Traditionally, spectrum is allocated to a communications service, e.g. terrestrial television broadcast, fixed satellite links, fixed land based systems, etc. Once allocated to a service, specific frequencies are assigned to individual users of the service. The allocation and assignment of spectrum is a long and arduous process, primarily to insure the 'best' use of a limited resource and to avoid interference between users. The avoidance of interference is extremely important to life-support services for example, hospital monitoring equipment, aircraft navigation, and flight control. Many government agencies responsible for critical services are hesitant to allow even very low levels of interference into their allocated spectrum.

Spectrum management is further complicated when considering global operation, as the Department of Transportation, Department of State, Department of Defense, and other government organizations must. Spectrum is considered a national resource by each sovereign nation. Coordination of spectrum between nations is handled by treaty and that implies the Department of State and the United States Senate are involved. Each nation retains the rights to allow or disallow use of radio frequency spectrum within their borders. Many sovereign nations will not allow any RF emanations outside proscribed radio frequency bands. Traditional UWB systems cannot meet those regulations.

The NC-OFDM approach we developed can work within the regulations and limitations on a global basis. Our proposed NC-OFDM system can place carriers in unused portions of the spectrum on a local basis and within legal constraints. We can detect interference in the environment and avoid that interference. We can avoid interfering with critical signals such as, GPS or other legacy communications. And, we can adapt to the propagation environment and mission requirements.

Figure 1 illustrates a single OFDM carrier and multiple OFDM carriers. A single carrier is at a specific center frequency and has some bandwidth based on the modulation of the carrier. Simple and low-rate modulation, e.g. On/Off keying will generate a narrow signal. A more complex modulation technique or higher-rate modulation will generate a slightly wider signal. OFDM systems typically de-multiplex a high-rate symbol stream across many low-rate carriers. This allows carriers to be placed very close to frequency band edges and, with suitable signal processing, within available spectrum gaps.

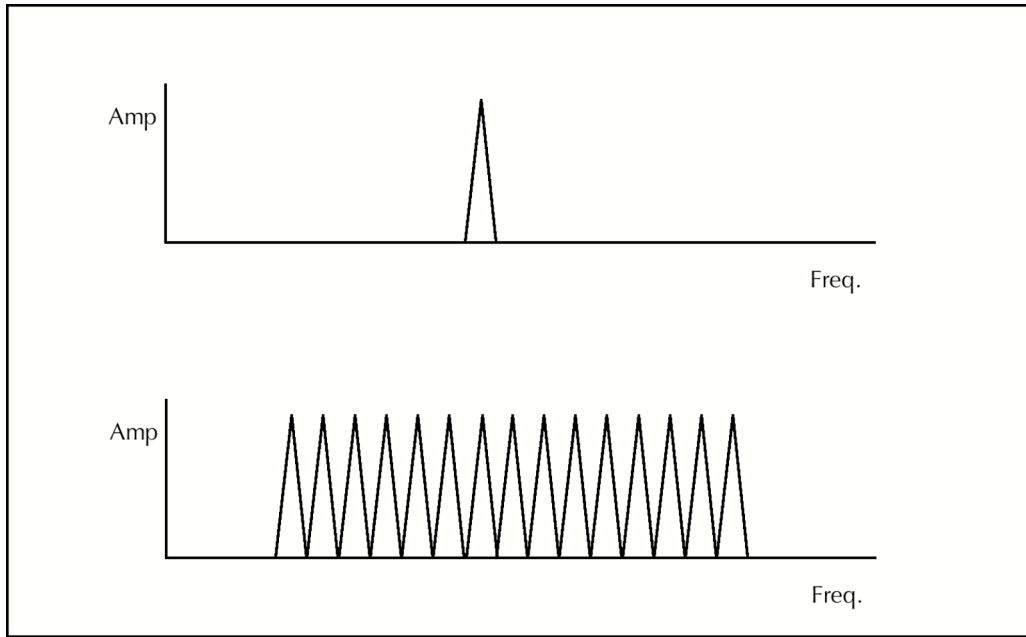


Figure 1 shows a single OFDM carrier and multiple OFDM carriers.

Generally, OFDM systems place a set of carriers, closely spaced, within a frequency band. This approach is used in IEEE 802.11a wireless Ethernet and IEEE 802.16 WiMax, and is proposed for advanced television broadcast. The goals in these systems are to (a) fully utilize the allocated band without interfering with adjacent bands, (b) simple channel equalization, and (c) work within existing rules for frequency allocation and assignment. Our proposed system places OFDM carriers at unused frequencies at irregular intervals. This enables our NC-OFDM system to take advantage of unused spectrum, but under full control of the radio system to comply with regulations.

Production of a NC-OFDM signal is the combination of hundreds to thousands of individual carriers at frequencies compatible with the requirements of the propagation environment, existing signals, and the regulations of the host country. OFDM is selected because one can move carriers with relative ease, one can move carriers very close to existing channels, and one can easily control the modulation and bandwidth. This concept is illustrated in Figure 2.

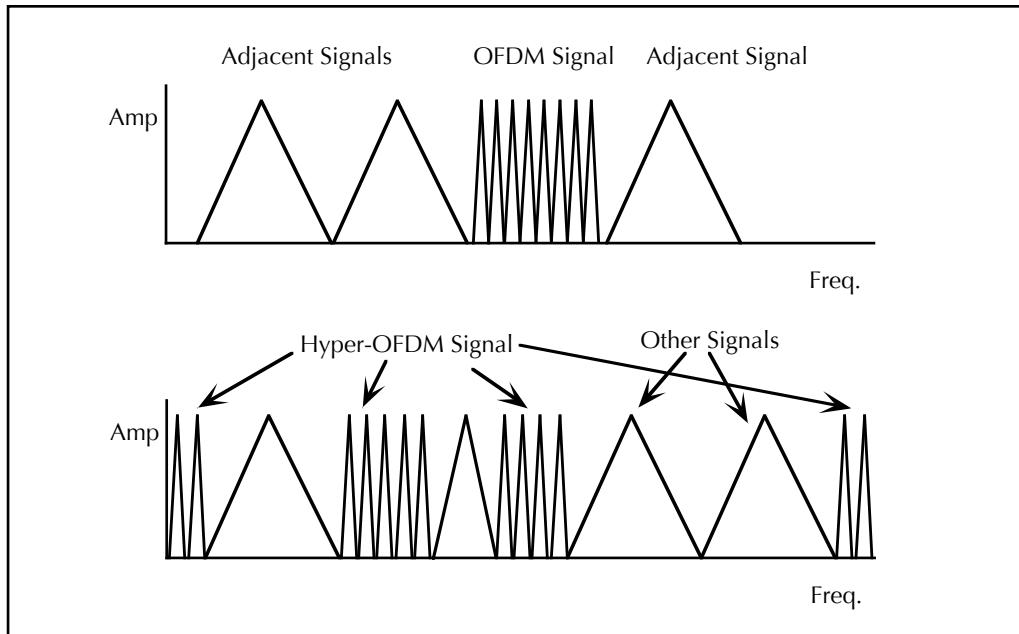


Figure 2 illustrates typical OFDM carrier placement and our proposed NC-OFDM carrier placement.

## 1.2 Research Approach, Architecture, and Prototype of a Flexible Wireless System

Our research objectives were five fold:

1. Develop and demonstrate ultra-wideband radio frequency transmitters and receivers.
2. Develop and demonstrate high-performance digital signal processing (DSP) algorithms and components to generate and detect NC-OFDM signals.
3. Develop and demonstrate ultra-wideband antennas, power amplifiers, and low-noise receivers to support the NC-OFDM system.
4. Analyze and evaluate of NC-OFDM signals for communication systems.
5. Determine how to recognize and organize NC-OFDM systems into a coherent network.

The system we designed and constructed is composed of three components:

1. Ultra-wideband radio frequency transmitters and receivers.
2. Ultra-wideband antennas, power amplifiers, and low-noise receivers to support the NC-OFDM system.
3. High-performance digital signal processing (DSP) algorithms and components to generate and detect NC-OFDM signals.

## 2 Building the KU Agile Radio

The Flexible Wireless System is built around a software defined radio (SDR) [Tuttlebee2002, Reed2002]. In a SDR, the majority of the signal processing is executed in field programmable gate arrays (FPGAs), digital signal processors (DSPs), general purpose processors (GPPs), or a combination of these. In addition to signal processing, a SDR usually has a control processor that manages radio control and operation. The architecture of a typical SDR is illustrated in Figure 3.

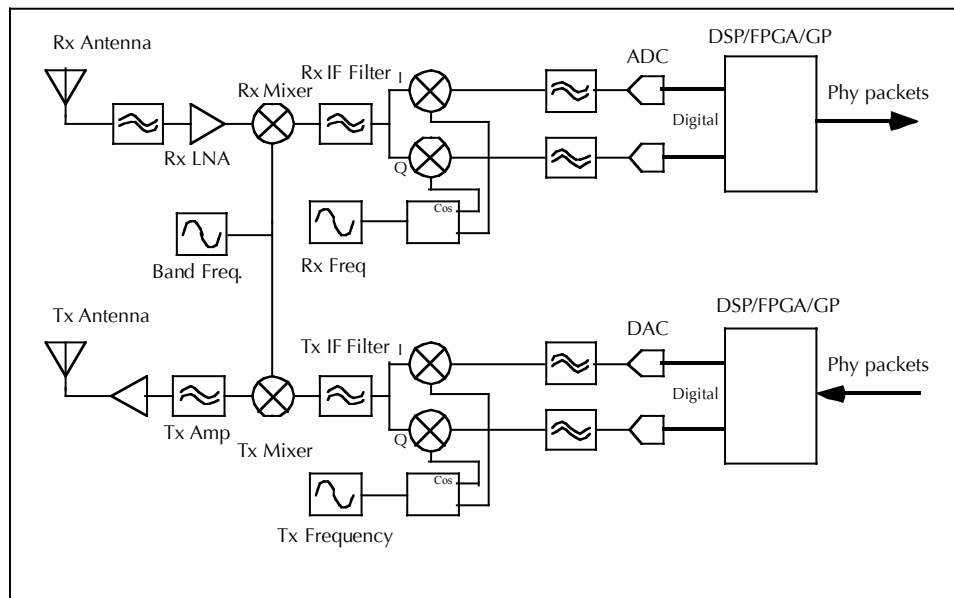


Figure 3 shows the architecture of a typical software defined radio.

In a typical SDR, radio signals are converted to/from the operating band to a base-band with an RF transceiver. Base-band signals are converted from analog format to digital format with analog to digital converters (ADCs) and from digital format to analog format with digital to analog converters (DACs). In the digital domain the signals are processed by FPGAs, DSPs, or GPPs.

The KU Agile Radio (KUAR) is the software-defined radio we designed and constructed for this project.

The KUAR features a modular design consisting of a power supply, a digital processing board and a RF transceiver. The current version of the radio operates in the 5 – 6 GHz band (UNII) and is capable of implementing numerous modulation algorithms, media access protocols, and adaptation mechanisms. As shown in Figure 4, the KUAR consists of five major sub-systems on three printed circuit boards: (i) a power supply, (ii) a control processor (CP), (iii) a digital board (DB) with a programmable signal processor (FPGA), analog-to-digital (A/D) and digital-to-analog (D/A) converters, (iv) an RF transceiver, and (v) antennas. With the exception of the antennas, the sub-systems are contained within a shielded box approximately 7 inches tall, 3 inches wide, and 6 inches deep, or roughly the size of a good dictionary.

A modular design was chosen so that sections of the KUAR platform can interoperate with other third party prototypes for purposes of experimentation and testing. For example, the KUAR CP and DB could be connected to other RF transmitters or receivers, to allow investigation of other frequency ranges or channel parameters. Alternatively, the KUAR active antennas and RF transceiver could be used with existing signal processing systems. In particular, the KUAR supports the GNU Radio [GNURadio] software system on the CP.

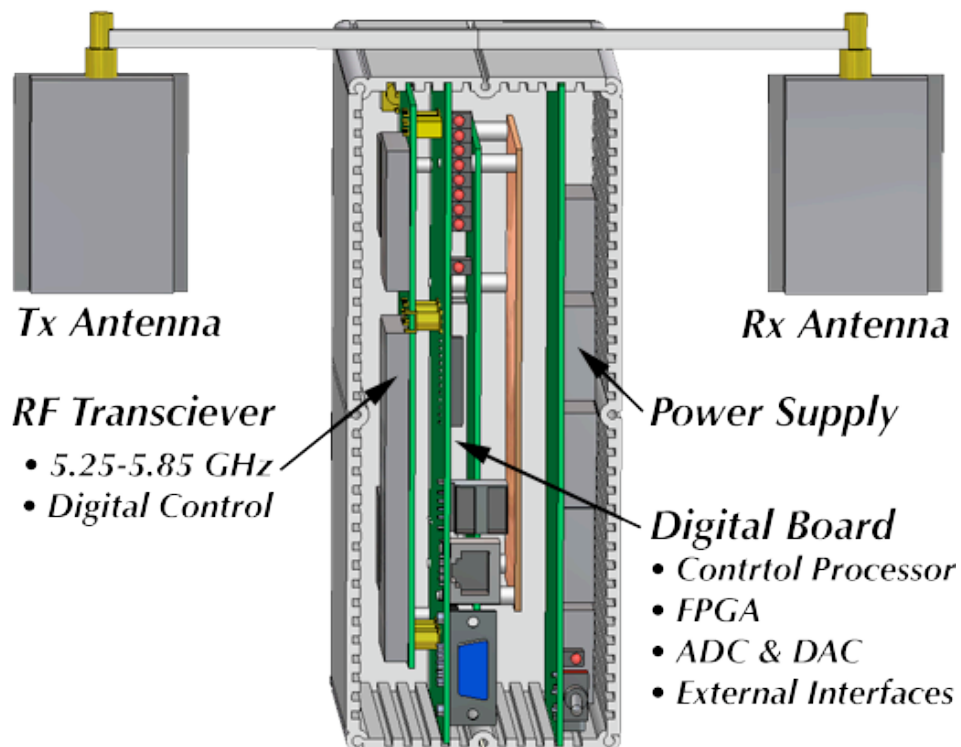


Figure 4 KUAR Radio

## 2.1 Power Board

The KUAR power supply is designed to run off of a 12 VDC battery or wall supply. This enables lab, mobile, and field deployment. The power board includes current sensors on each independent supply that are monitored by the CP.

## 2.2 Digital Board

The Digital Board contains the CP, an FPGA, A/D and D/A converters, and external interfaces. The organization of these components is shown in Figure 5.

The CP is an embedded PC operating at 1.4 GHz with 1 GB SDRAM and 6 GB micro-disk built on the COMExpress form factor. The CP uses PCI to interface with the FPGA. External interfaces include USB 2.0, VGA and PCI Express connections, and Gigabit Ethernet. The default operating system on the CP is Linux, however other operating systems could be employed. Linux provides common networking services and applications while Ethernet enables the radios to easily connect into existing laboratory networks or be used in standalone configurations. The processing power of the CP and FPGA enable experiments requiring rapid operational changes based on current RF environment measurements, quick changes of radio configuration, and significant signal processing.

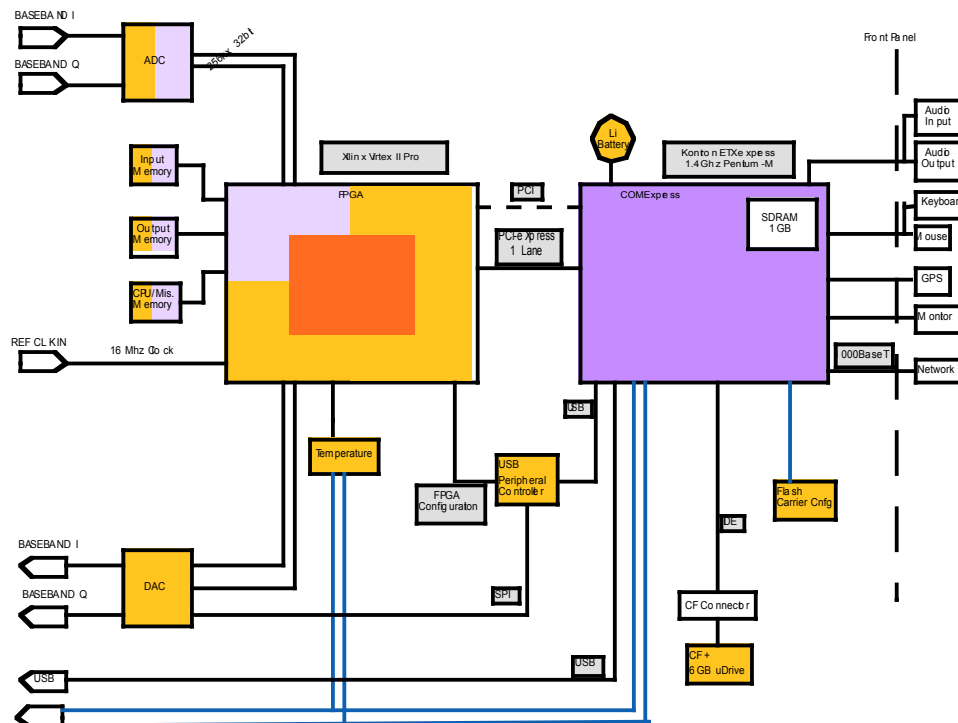


Figure 5 shows the KUAR Digital Board

The primary sub-system for signal processing operations is the FPGA. The KUAR uses a Xilinx Virtex II Pro P30 FPGA, which has 30,816 logic cells, two PowerPC 405 cores, and operates up to 350 MHz. The FPGA is directly connected to quadrature A/D and D/A converters, 4 MB of SRAM, and the CP. The KUAR provides significant flexibility to the researcher in locating signal processing functions in hardware logic, the embedded PowerPC processors or the CP, depending on the experimenter's interests and signal processing demands. The received quadrature signal is sampled at up to 105 megasamples per second with 14-bit resolution and the transmitted quadrature signal is converted at up to 160 megasamples per second with 16-bit resolution.

### 2.3 RF Transceiver

The RF transceiver, Figure 6, implements independent transmit and receive frequencies, digitally controlled transmit power outputs, and receive gain levels. The RF transceiver



uses standard RF connectors to allow the use of a variety of antenna types and configurations. Digital control of transmitter output power, receiver attenuation, and demodulator amplifier gain is useful for fading channel experiments and also allows automatic or programmed control.

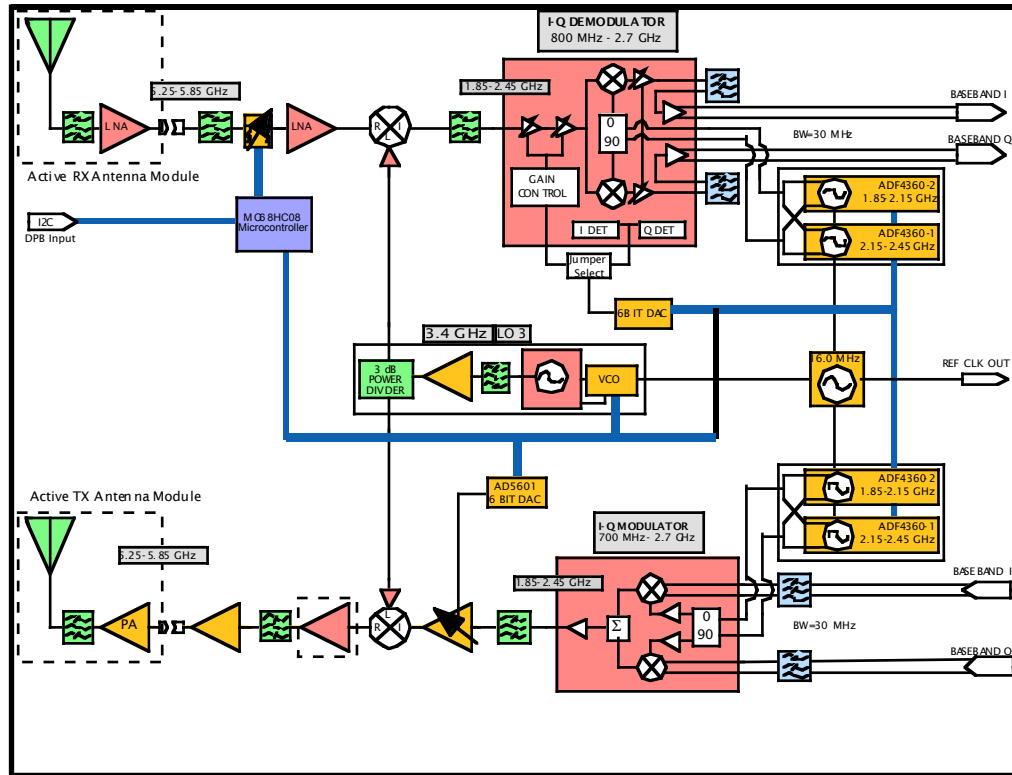


Figure 6 shows the KUAR RF transceiver.

The RF transceiver covers the frequency range of 5.25 - 5.85 GHz within the 5 GHz Unlicensed National Information Infrastructure (UNII) band. The receiver sensitivity with active antennas is -100 dBm and the transmit power with active antennas is up to +25 dBm.

The 5 GHz RF transceiver is a hybrid direct conversion design that makes use of a traditional superheterodyne frequency conversion to and from an intermediate frequency (IF) range of 1.85-2.45 GHz, which is directly converted to baseband using a quadrature demodulator, and from baseband using a direct conversion quadrature modulator. The RF transceiver is currently configured to select 30 MHz bands from between 5.25 - 5.85 GHz in 4 MHz tuning steps.

An 8-bit microcontroller unit (MCU) is used to interface the CP to the programmable components of the RF transceiver. The MCU translates commands from the CP to component control signals and returns status information from the RF transceiver to the CP.

## 2.4 Antennas

Three basic configurations of broadband 5 GHz directional planar antennas have been designed and constructed for the KUAR system – (i) basic passive, (ii) active receive (Rx), and (iii) active transmit (Tx). The passive antennas are intended for use in indoor or short range outdoor test environments, while the active versions utilize integrated RF amplification and filtering to provide longer range outdoor test performance. Example antennas are shown in Figure 7.

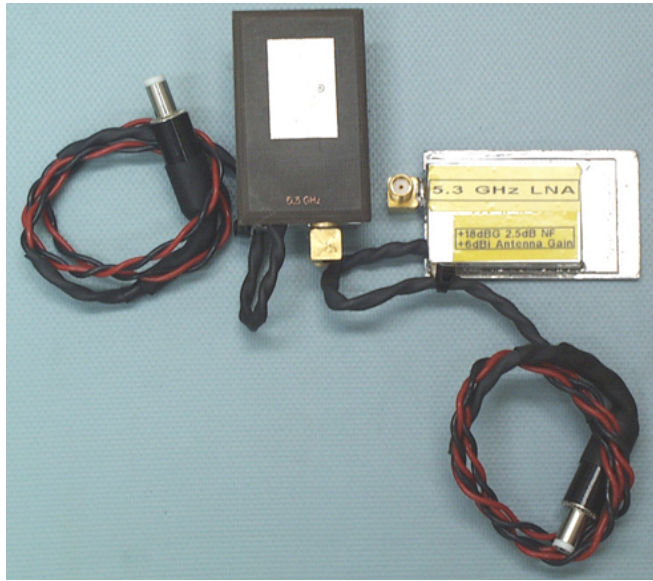


Figure 7 is a picture of the front and back of receiver antenna patches for the KUAR radio. The patches integrate an antenna, bandpass filter, and low noise amplifier into a modular package. These patches can be combined into many different antenna configurations. The antennas are 6.5 cm long, 3.5 cm wide, and 1 cm thick.

Full details of the KUAR design are available in the technical reports.

## 3 Project Structure

During the project we constructed models, analyses, and hardware for the KUAR. This work is described in a set of technical reports described in Table 1 and available from the Information and Telecommunications Technology Center.

ITTC-FY2008-31620-01	Gary Minden Joseph Evans	STI: Flexible Wireless Systems for Rapid Network Evolution: Final Report (This report)	January 2008
ITTC-FY2008-31620-02	Dan DePardo, Gary Minden Joseph Evans	KU Agile Radio 5 GHz 3.0 RF Module Description	July 2007
ITTC-FY2008-31620-03	Leon Searl Gary Minden Joseph Evans	Agile Radio Digital Board Design Version 3.0 Rev. 0	February 2007
ITTC-FY2008-31620-04	Anupama Veeragandham	OFDM Testbed Analysis and Implementation Framework	September 2007
ITTC-FY2008-31620-05	Rakesh Rajbanshi	OFDM-Based Cognitive Radio for DSA Networks	September 2007
ITTC-FY2008-31620-06	Jordan Guffey	OFDM Physical Layer Implementation for the Kansas University Agile Radio	February 2008
ITTC-FY2008-31620-07	Brian Cordill	Automated RF Testing of the KU Agile Radio 2.0 using LabView	February 2008

**Table 1 lists the KUAR Technical Reports. The reports are available at <http://www.ittc.ku.edu>.**

### 3.1 Participants

The project supported the following faculty in EECS: G. Minden and J. Evans.

The project also supported Mr. Leon Searl and Mr. Dan DePardo, members of our technical staff.

### 3.2 Graduate Student Training

We placed a strong emphasis on disciplined, engineered system and software design and development. Mr. Searl and Mr. DePardo brought many years of industrial experience to the project and closely worked with the students to develop the student's skills. All students were required to write (and re-write) component requirements, specifications, design, test, and presentation documents. We strongly emphasized the written, communication, documentation, and correct operation of KUAR software systems. Students who participated in KUAR have a strong grounding in the research development process and necessary skills in team operations.

The following graduate students worked on the project: Anupama Veeragandham, Tim Newman, Jordan Guffy, Dragan Trajkov, Ted Weidling, Qi Chen, Dinesh Datla, Rakesh Rajbanshi, Ryan Reed, Preeti Krishnan, V. Rory Petty.

The following students worked on the project as undergraduates: Ted Weidling, Travis Short, V. Rory Petty, Megan Lehnerr, and Brian Cordill.

## **4 Publications**

### **4.1 Book Chapters**

R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "OFDM-Based Cognitive Radios for Dynamic Spectrum Access Networks," *Cognitive Radio Communications Networks* (Vijay Bhargava and Ekram Hossain, Eds.), Springer-Verlag, 2007.

R. Rajbanshi, A. M. Wyglinski, and G. J. Minden, "Peak-to-Average Power Ratio Reduction of Multicarrier Transceivers," *Encyclopedia on Wireless and Mobile Communications* (Borko Furht, Ed.), CRC Press, 2007.

### **4.2 Journals**

T. R. Newman, B. A. Barker, A. M. Wyglinski, A. Agah, J. B. Evans, and G. J. Minden. "Cognitive Engine Implementation for Wireless Multicarrier Transceivers," *Wiley Journal on Wireless Communications and Mobile Computing*, Vol. 7, No. 9, Pgs. 1129-1142, Nov. 2007.

G. J. Minden, J. B. Evans, L. Searl, D. DePardo, R. Rajbanshi, J. Guffey, Qi Chen, T. Newman, V. R. Petty, F. Weidling, M. Lehnerr, B. Cordill, D. Datla, B. Barker, A. Agah, "An Agile Radio for Wireless Innovation," *IEEE Communications Magazine*, IEEE, Vol. 45, No. 5, May 2007.

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Timothy R. Newman, Rakesh Rajbanshi, Alexander M. Wyglinski, Joseph B. Evans, and Gary J. Minden. *Population Adaptation for Genetic Algorithm-based Cognitive Radios*. Accepted for publication in the *ACM/Springer Mobile Ad Hoc Networks -- Special Issue on Cognitive Radio Oriented Wireless Networks and Communications*, 2008.

### **4.3 Conference**

F. Weidling, D. Datla, V. Petty, P. Krishnan, G.J. Minden, "A Framework for R.F. Spectrum Measurements and Analysis," *IEEE DySPAN 2006*, Baltimore, MD, Nov. 8-11, 2005. (Poster)

T. Newman and G.J. Minden, "A Software Defined Radio Architecture Model to Develop Radio Modem Component Classifications," IEEE DySPAN 2006, Baltimore, MD, Nov. 8-11, 2005. (Poster)

G. D. Troxel, E. Blossom, S. Boswell, M. Brodsky, A. Caro, I. Castineyra, A. Colvin, T. Dreier, J. B. Evans, N. Goffe, K. Haigh, T. Hussain, V. Kawadia, D. Lapsley, C. Livadas, A. Medina, J. Mikkelson, G. J. Minden, R. Morris, C. Partridge, V. Raghunathan, R. Ramanathan, C. Santivanez, T. Schmid, D. Sumorok, M. Srivastava, B. Vincent, D. Wiggin, A. M. Wyglinski, and S. Zahedi, "Adaptive Dynamic Radio Open-source Intelligent Team (ADROIT): Cognitively-controlled Collaboration among SDR Nodes," Proceedings of the IEEE Communications Society Conference on Sensors, Mesh and Ad Hoc Communications and Networks (SECON) - Workshop on Networking Technologies for Software-Defined Radio Networks (Reston, VA, USA), September 2006 (INVITED).

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Dinesh Datla, Rakesh Rajbanshi, Alexander M. Wyglinski, and Gary J. Minden, "Parametric Adaptive Spectrum Sensing Framework for Dynamic Spectrum Access Networks," Proceedings of the Second IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (Dublin, Ireland), April 2007.

Timothy Newman, Rakesh Rajbanshi, Alexander M. Wyglinski, Joseph B. Evans, and Gary J. Minden, "Population Adaptation for Genetic Algorithm-based Cognitive Radios," Proceedings of the Second International Conference on Cognitive Radio Oriented Wireless Networks and Communications (Orlando, FL, USA), August 2007.

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## 5 Conclusion

We designed and implemented a flexible wireless radio suitable for radio network experimentation. We introduced the concept of a non-contiguous OFDM system, produced simulations, analyses, and implementation of such a system.

Our wireless system, the KU Agile Radio (KUAR), is a solid platform for future wireless research. We demonstrated the KUAR at international conferences. It's flexibility enables wireless networking experiments well beyond the conventional 802.11 based, ad hoc (MANET) experiments. The wideband nature and programmability of the KUAR introduces more opportunities into our exploration of wireless, mobile networking, but at the same time the increased need to understand the dynamic and distributed allocation of the radio frequency resource.

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