Radio Links for the NASA ABTS

Final Report
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11 December 1996
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Radio Links for the NASA ABTS:

NASA University Consortium Grant REF# 96-108
Project Dates: 5 DEC 95 to 4 DEC 96

Contract # NCC2-5108

Final Report
### Goals

- Determine Out-Link FSK Bandwidth
- Develop FSK Outlink Transmitter
- Develop Wideband Outlink FSK Receiver
- Develop OOK In-Link Transmitter
- Develop OOK In-Link Receiver
- Marry Out-Link & In-Link Components

- Outlink FSK Bandwidth preliminary inlink transmitter were accomplished in Summer 1995 visit. The calculation of FSK bandwidth is repeated in these notes. Spectrum analyzer measurements of the actual FSK spectrum agree well with the calculations.

- The goal to develop a wideband FSK receiver for outlink data was given first priority for end of Summer 1996 completion.

- The goal of developing OOK inlink transmitter and receiver system components and interfacing all outlink and inlink components into an operating closed loop prototypical system was given a December 1, 1996 completion date.
**System Overview**

- **FSK** selected for good data reliability and straightforward implementation of biotelemeter and outlink receiver
- **Out-Link Data** is sent *from* the biotelemeter
- **In-Link Data** is sent *to* the biotelemeter
- **Carrier Frequencies**: 174 - 216 MHz.

**FSK** (Frequency Shift Keying) of the biotelemeter RF transmitter is selected for straightforward implementation of the biotelemeter transmitter circuit and outlink receiver configuration, and good data reliability.

**Outlink Data** is PCM formatted with header, data, and checksum packets in each data frame. The PCM signal is generated by the biotelemeter microcontroller and FSK modulates the biotelemeter RF carrier. The data rate is about 49.1 kb/s (24.6 kHz) for 8 data channels, when each is sampled at 256 samples/s.

**Inlink Data** is PCM formatted with header, data, and checksum packets in each data frame. The PCM signal is presently generated by the personal computer connected to the outlink receiver/inlink transmitter serial port. The PCM data On Off Keys (OOK) the 433.94MHz inlink transmitter at 19.2 kb/s (38.4 kHz).

**Carrier Frequencies** A.R.C. has selected for the biotelemeter outlink signals lie in the biomedical band 174 to 216MHz. See the "ABTS Band Plan" slide.
The **ABTS Band Plan** is arranged according to ABTS requirements ("Final Report, Animal Biotelemetry System Feasibility Study", L. Edsinger and J. Schonfeld, August, 1994).

Note that the example frequencies are within the FCC designated band for wireless biomedical devices and share these frequencies on a non-interfering/accept interference basis with other radio services. The primary users of 174 - 216 MHz frequencies are television broadcasters. Therefore all biotelemetry systems that use this band must choose frequencies accordingly. This may not present any problems in a space setting but it would be prudent to study the occupancy of these frequencies in their target locations. (Including fundamental and harmonic energy that might fall in the band).

In addition to the example fundamental ABTS operating frequencies and “channels”, first Local Oscillator and Image frequencies are shown in the slide above for later discussion.
Outlink Bandwidth Calculations

- Packet Rate
- Packet Length
- Baud Rate
- Signal Bandwidth

**Packet Rate**
Maximum 8 Data Channels + Header and Checksum = 256 Samples/s per channel

**Packet Length**
1 byte (header) + 16 bytes (data) + 1 byte (checksum) = 18 bytes/packet
8 bits (data) + 2 bits (start & stop) = 10 bits/byte
18 bytes/packet X 10 bits/byte = 180 bits/packet

**Baud Rate**
180 bits/packet X 256 packets/s = 49.1 kb/s
The apparent data rate then is 24.6 kHz

**Signal Bandwidth**
\[ BW = F_{\text{MOD}} \left[ 2\beta + 1 \right] \] (Carson’s Theorem)
Choose Modulation Index = 5 (Allows 5 harmonics)
So signal BW = 24.6 kHz X 11 = 270 kHz
### Out-Link Receiver Features

- **Frequency coverage**: 174 - 216 MHz
- **Synthesized**: 0.01, 0.1, 1, 2 MHz steps
- **Dynamic Range**: BDR=67dB; IMD-DR=87dB
- **MDS**: -115 dBm (SINAD)
- **I.F. Bandwidth**: 280 kHz
- **Outputs**: PCM; RSSI; Detector; PLL; Squelch
- **Compatibility with other biotelemetry systems**
Receiver Block Diagrams

- Receiver RF Subsystem
- Microcontroller Subsystem
- Frequency Synthesizer
- Power Supplies and Audio Output

See following four slides
Receiver RF Subsystem

- Broadband Match
- GaAs FET Amplifier
- Image Rejection Filter
- Tuning Voltage
- Frequency Synthesizer
- 244-288 MHz, First L.O.
- Voltage Controlled Oscillator
- Down Converter
- MMIC I.F. Amplifier
- Frequency Programming from Microcontroller VCO Board
- 80.7 MHz, Second L.O.
- Wideband FM IF Subsystem
  - MC13158
  - Second I.F. Filter
  - FO = 10.7 MHz
  - BW = 280 kHz
- SAW Band Pass Filter
  - FO = 70 MHz
  - BW = 280 kHz
- Outputs
  - Squelch
  - RSSI
  - PCM Data Detector
  - PLL Lock
Note that the Image Rejection Filter tuning voltage and the AGC (Automatic Gain Control) voltage can be readily provided by DAC's (Digital to Analog Converter) under microcontroller supervision. In the present receiver implementation these voltages are supplied by potentiometers. The tuning voltage is buffered and available to external preselector filter and preamplifier. This allows tuning the complete system with just one frequency command input.
The *Frequency Synthesizer* is of conventional design.

- The MC45152 PLL is a CMOS device and the MC12016 is an ECL device.
- The Loop Filter is a 3rd order filter that was designed and modeled using PSPICE.
- An LF351 FET input operational amplifier is the active device in the filter.
- The PLL Lock Detector is a pulse integrator and comparator circuit using a single supply operational amplifier for the active device. A PLL lock indication is provided by a green LED on the receiver's front panel.
- Loop lockup time is about 10 ms for 2 MHz steps

The *frequency programming procedure* for the synthesizer is detailed in the following two slides.
Power Supplies and Audio Output

15 - 28 VDC
POWER INPUT

Power Consumption:
\[ V_{in} = 15 \text{VDC} \]
\[ I_{in} = 280 \text{mA} \]
\[ P_{in} = 4.2 \text{W} \]

12 VDC REGULATOR

5 VDC REGULATOR

Regulated 12VDC to Receiver RF and Frequency Synthesizer Subsystems
Regulated 5VDC to Microcontroller Subsystem

Audio from FM IF Subsystem

AUDIO VOLUME Potentiometer

12 VDC REGULATOR

5 VDC REGULATOR

AUDIO AMPLIFIER

Audio from FM IF Subsystem
**Frequency Programming Procedure**

- Uses Motorola MC145152 PLL
- \( F_{RX} = 174 \text{ to } 216\text{MHz and } F_{IF} = 70\text{MHz} \)
- \( F_{LO} = 244 \text{ to } 286\text{MHz} \)
- 2-Modulus Prescaler with 40/41 Divide
- \( F_{STEP} = F_{REF} = 10\text{kHz} \)
- Clock Divide Value = 1024 so
  \( F_{XTAL} = 10.240\text{MHz} \)

- MC145152 PLL has \( N \) and \( A \) registers
- Registers are loaded in parallel from two latches
- Total divide value = \( N_T = N \times P + A \)
- \( N_T = F_{LO} / F_{STEP} = F_{LO} / 10\text{kHz} \)
- Use MC12106 ECL Divider with \( P = 40 \)

**Example:** Let \( F_{RX} = 195.09 \) so \( F_{LO} = 265.09\text{MHz} \)

**Step 1:** Set \( A = 0 \):

\[
N_{TOT} = 265.090 / 0.010 = 26509 \\
N_{10} = 26509 / P = 26509 / 40 = 662.725
\]

**Step 2:** Take Integer part of \( N_{10} \): \( N_{10} = 662 \)

**Step 3:** Convert \( N_{10} = 662 \) to binary:

\( N_2 = 1010010110 \)

**Step 4:** Find \( A = N_{TOT} - N \times P \)

\( A_{10} = 26509 - 662 \times 40 = 29 \)

**Step 5:** Convert \( A_{10} = 29 \) to binary:

\( A_2 = 011101 \)

**Step 7:** Program Microcontroller to Generate \( N \) and \( A \) from

Optical Encoder Receiver Frequency Adjust

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**Synthesizer Design Spreadsheet**

- Design Aid for PLL Programming
- Uses High-Side Local Oscillator Injection
- For Dual and Single Modulus Prescalers
- Enter Receiver Frequency Range, Frequency Step Size, I.F., Prescale Value, Clock Divide Value
- Spreadsheet shows N and A Register Programming values in Decimal and Binary

### NASA ABTS RECEIVER - PLL Programming

**HIGH SIDE INJECTION**

Enter frequency step size, (Fstep) kHz: 10
Enter Lowest input receive freq, (Fmin) MHz: 174
Enter Highest input receive freq, (Fmax) MHz: 216
Enter Receiver I.F., MHz: 70
Enter prescale value, (P): 40
Enter TABLE (below) increment, kHz: 2000

<table>
<thead>
<tr>
<th>Receive, MHz</th>
<th>LO, MHz</th>
<th>N (base 10)</th>
<th>A (base 2)</th>
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<td>218.00</td>
<td>328.000</td>
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</table>

Manual Calculation: Enter Recevive Frequency, MHz = 195
Each of these *Receiver Performance Tests* are detailed in the following slides and notes.
Dynamic Range

- Dynamic Range measures the ability of a receiver to function correctly in the presence of strong signals outside its passband.
- For the ABTS outlink receiver, DR is:
  » Blocking Dynamic Range (BDR) = 67 dB
  » IMD Dynamic Range (IMD DR) = 87 dB

**Blocking Dynamic Range Measurement Procedure:**
Receiver tuned to 195 MHz. Signals applied to the receiver from two sources via a combiner at 195 MHz and 193 MHz. Measurements were made with a spectrum analyzer at the first IF SAW filter output. The signal power at 193 MHz was increased until a 1 dB gain compression was noted.

At 195 MHz $P_{\text{IN}} = -59$ dBm. At 193 MHz $P_{\text{IN}} = -58$ dBm caused 1 dB compression.

Noise floor: -125 dBm at 195 MHz brings the signal 3 dB above baseline noise so the noise floor is -125 dBm
Therefore $BDR = -58$ dBm - (-125 dBm) = 67 dB

**IMD Dynamic Range Measurement Procedure:**
Apply 195 and 197 MHz signals, equal amplitude, to the receiver. Increase both amplitudes simultaneously until the 3IMD product increases 3 dB above the noise floor.

$P_{\text{IN}} = -38$ dBm resulted in the 3 dB increase in 3IMD

Therefore: IMD DR = -38 dBm - (-125 dBm) = 87 dB
Intermodulation Distortion occurs when a strong signal nearby in frequency to the desired signal combines with the desired signal to generate unwanted products (especially those close-by the desired signal frequency) that can cause interference. It is the non-linear operation of amplifiers, etc. that cause generation of IMD products.

The "close-in" unwanted signals are called the third order distortion products or 3IMD. They occur at $2F_2 - F_1$ and $2F_1 - F_2$.

The results shown in the slide above were obtained by applying equal amplitude unmodulated carriers (-40dBm) simultaneously to the receiver from two signal sources combined with a 2-way, $0^\circ$ combiner (Mini-Circuits ZSC-1, 4db insertion loss). F1 was 195 MHz and F2 was 197 MHz with 3IMD products at 193 and 199 MHz. Second order responses at 390, 394, 784, and 4 MHz were not significant.

A figure of merit for IMD is the 3rd order intercept point (3 OIP). It was calculated from the 3IMD measurements as follows:

$$IP_3 = \frac{n \times P_A - P_{IMn}}{n-1}$$
At 193 MHz:

\[ IP_3 = \frac{3 \times P_{F1} - P_{193}}{3 - 1} = \frac{-117 + 75}{2} = -21 \text{ dBm} \]

At 199 MHz:

\[ IP_3 = \frac{3 \times P_{F1} - P_{199}}{3 - 1} = \frac{-117 + 78}{2} = -19.5 \text{ dBm} \]

Measurements were made at the first mixer input using a Tektronix 495P Spectrum Analyzer.
**Procedure for S+N+D Measurement:**

Apply 194MHz FM signal with 125kHz deviation, 1kHz sine baseband to the receiver. Measure S+N+D voltage (rms) at the detector output as $P_{IN}$ is increased from -127 dBm.

**Procedure for N+D Measurement:**

Apply 194MHz unmodulated signal to the receiver. Measure S+N+D voltage (rms) at the detector output as $P_{IN}$ is increased from -127 dBm.

**Minimum Detectable Signal (MDS):**

One measure of MDS is the input power (dBm) where the S+N+D is 3dB (i.e.: twice) the N+D. From the data:

$$\text{MDS} = -115 \text{ dBm}$$

S+N+D and N+D detector output voltage measurements were made with a HP-311A Audio Distortion Analyzer.
With high-side injection of the first L.O. the *First IF* is:

\[ F_{IF1} = | F_0 - F_{LO1} | = | 195 - 265 | = 70 \text{ MHz} \quad (F_{LO1} > F_0) \]

The important *Image Frequency* is:

\[ F_{IMG} = F_0 + 2 \times F_{IF1} = 195 + 2 \times 70 = 335 \text{ MHz} \]

**Measured Image Rejection Procedure:**

Apply \( F_0 \) at \( P_0 \) then \( F_{IMG} \) at \( P_{IMG} \) to the Receiver Input

Output Reference: -50 dBm at the 70 MHz SAW I.F. Output

**Results:**

At \( F_0 = 195 \text{ MHz} \)
\( P_0 \) was -105 dBm

At \( F_{IMG} = 335 \text{ MHz} \)
\( P_{IMG} \) was -32 dBm

Therefore the *Measured Image Rejection* = \( P_0 - P_{IMG} = -73 \text{ dB} \)

*See the "ABTS Band Plan" slide for complete Image frequency data*
With high-side injection of the second L.O. the *Second IF* is:

\[ F_{\text{IF2}} = | F_{\text{IF1}} - F_{\text{LO2}} | = | 70 - 80.7 | = 10.7 \text{ MHz} \quad (F_{\text{LO2}} > F_{\text{IF1}}) \]

The important *Image Frequency* is:

\[ F_{\text{IMG}} = F_{\text{IF1}} + 2 \times F_{\text{IF2}} = 70 + 2 \times 10.7 = 91.4 \text{ MHz} \]

**Measured Image Rejection Procedure:**

Apply \( F_{\text{IF1}} \) at \( P_{\text{IF1}} \) then \( F_{\text{LO2}} \) at \( P_{\text{LO2}} \) to the Receiver Input

Output Reference: -60 dBm at the 10.7 MHz I.F. Amplifier Output

**Results:**

- At \( F_{\text{IF1}} = 70 \text{ MHz} \) \( P_{\text{IF1}} \) was -105 dBm
- At \( F_{\text{IF2}} = 91.4 \text{ MHz} \) \( P_{\text{IF2}} \) was -32 dBm

Therefore the *Measured Image Rejection* = \( P_{\text{IF1}} - P_{\text{IF2}} = -73 \text{ dB} \)
Receiver Spur Analysis

Spurious Response analysis identifies the frequencies and approximate levels of spurious signals that might be generated by the first mixer. This analysis aids in the choice of first IF frequency. The table shows acceptable spur levels for a 70 MHz IF for the receiver.
**Receiver I.F. Rejection**

- **Measured First I.F. Rejection:**

- **Measured Second I.F. Rejection:**

**Measured First I.F. Rejection Procedure:**

Apply $F_0$ at $P_0$ then $F_{IF1}$ at $P_{IF1}$ to the Receiver Input

Output Reference: -50 dBm at the 70 MHz SAW I.F. Output

**Results:**

At $F_0 = 195$ MHz \( P_0 \) was -105 dBm
At $F_{IF1} = 70$ MHz \( P_{IF1} \) was -7 dBm

Therefore the **Measured First I.F. Rejection** = $P_{IF1} - P_{IF2} = -98$ dB

**Measured Second I.F. Rejection**

Apply $F_0$ at $P_0$ then $F_{IF2}$ at $P_{IF2}$ to the Receiver Input

Output Reference: -60 dBm at the 10.7 MHz I.F. Amplifier Output

**Results:**

At $F_0 = 195$ MHz \( P_0 \) was -105 dBm
At $F_{IF2} = 10.7$ MHz \( P_{IF2} \) was > 0 dBm

Therefore the **Measured Second I.F. Rejection** = $P_0 - P_{IF2} > -105$ dB
**RSSI**

**RSSI Dynamic Range:**
The approximately linear RSSI range is -120 dBm to -40 dBm
so the RSSI Dynamic Range is 80 dB

**RSSI Sensitivity:**
The RSSI Sensitivity is the slope of the RSSI Output Voltage vs. Signal
Input Level curve:

$$\text{Sensitivity} = \frac{1.7V}{80\text{dB}} = 21.25 \text{ mV per dB}$$
Receiver I/O Signals for External Use

- PC Control
- Detector Output
- RSSI Output
- Conditioned PCM Data
- Squelch
- PLL Lock Indication

- **PC Control** provides I/O in RS-232 format via a rear apron DB-9 connector. This is presently configured for connection to a personal computer for receiver control and biotelemeter programming and for display of decoded physiologic signals. The enabling software is a WINDOWS application designed by J. Carter.

- **Detector output** provides a voltage proportional to a biotelemeter frequency variation from a programmed frequency. In the event that a biotelemeter slowly drifts after implant this signal can be used to retune the outlink receiver (within an established range).

- **RSSI output** is a voltage that indicates the strength of the received biotelemeter signal. It could be used in conjunction with other received data parameters to suggest animal activity; it is an immediate indication of a signal dropout. It also provides a demodulated AM output for potential use with biotelemeters of other manufacture.

- **Conditioned PCM data** is the data presented to the inlink transmitter.

- **Squelch** is a high (carrier strength acceptable) or low (carrier too weak) voltage determined by an adjustable threshold. It is useful for disabling external circuits so that they are not presented with noise.

- **PLL Lock indication** is a voltage (High or Low) that reveals the lock status of the PLL in the frequency synthesizer.
**Receiver Usability with Other Biotelemetry Systems**

- Frequency Coverage 174 to 216 MHz
- PCM Data Output from FSK:
  - Buffered Raw data from FM Detector
  - Personal Computer Formatted (RS-232)
- PCM Data Output from PAM:
  - Buffered Raw Data from RSSI
  - Data BW = 3 kHz

The receiver design provides the flexibility for operation with a variety of FSK, FM, and AM biotelemeters using PCM, PIM, PPM, etc. pulse formatted time multiplexed encoding.
Team Involved

- Marquette University -
  » Andrea Biegel - Research Assistant
  » Aaron Jeutter - Receiver Micro Programmer
  » Dean Jeutter - RF Circuit Design
- Triomed Electronics -
  » Jerry Carter - WINDOWS GUI PC Software
  » Mark Geisler - Software Development for the Biotelemeter Microcontroller
Next Steps

- Summary: A functional Closed Loop prototype demonstrates the feasibility of the ABTS approach.
- Future:
  » Habitat/Glove box/Centrifuge projects
  » Biotelemetry System
  » Needed from ARC Group

Summary:
The closed loop prototype has operational bi-directional wireless links. The Wideband PCM-FSK receiver has been designed and characterized. Now that both links function, communication performance can be addressed. For example, noise problems with the received outlink signal that caused the PC program to lockup were just recently revealed and minimized by software "enhancements" to the Windows based PC program.

A similar problem with inlink communication was uncovered several days before this report: A noise spike or dropout (expected events in the animal Habitat) caused an interrupt to the implant microcontroller which halted outlink transmission. Recovery of outlink transmission did not reliably occur. The problem has been defined and implant software is being modified to better recognize noise from data by changing the timing associated with valid data packet identification and by better utilizing the error flags generated by the microcontroller's SCI circuits.

Excellent inlink performance will also require improvements in the implant's receiver. The biggest performance improvement can be provided by antenna design for the Habitat. The quarter wavelength whip antennas used with the demo prototype inlink leave much to be desired.

Future: See Next Three Slides
Future:
Habitat, Glovebox, Centrifuge

- Install system in a Habitat, Glove box, centrifuge project
  - Parallel activities at both ARC and MU using identical systems
  - Interface RF subsystems with target enclosures' antennas
- Use appropriate enclosure antennas (e.g.: Dr. Philip Carter designs)

- An efficient approach to adapting the ABTS to the Habitat, Glove box, centrifuge project enclosures can be to provide MU with enclosures and antennas and at the same time provide ARC with ABTS components.

- The PCM-FSK receiver was design with a 50 Ohm broadband input. This was done to facilitate easy matching with an external low noise preamplifier and Habitat antenna (Dr. Carter's design). The preamplifier should have a preselector filter matched to the Habitat antenna. The preselector filter can be voltage tuned by the tuning voltage provided at the PCM-FSK receiver output connector. The addition of such a preamplifier can improve overall receiver performance (noise, IMD, dynamic range). Further, with the preamplifier located in close proximity to the Habitat antenna, and with a 50 Ohm coaxial connection to the remotely situated PCM-FSK receiver, overall receiver performance is expected to be excellent.

- The interfacing of the inlink RF with enclosure antenna(s) should be considered soon. The best situation would have one common antenna serving both inlink and outlink. This might require the development of duplexing circuits.
Future: Biotelemetry System

- Biotelemeter
- Outlink Receiver
- Inlink Transmitter
- Inlink Receiver

**Biotelemeter**
- Prune PCM frame, compress PCM data, and implement new microcontroller (Microchip Corp. PIC Processor) for decreased biotelemeter power consumption
- Finalize implant RF transmitter - minimize power
- Crystal control the implant’s transmitter. The CTS-Marden Crystal Manufacturing Co. (Burlington, WI) was contacted recently to discuss the possibility of fabricating a very miniature quartz crystal with fundamental oscillating frequencies available in the 174 - 216 MHz. biotelemetry band. Such a crystal would lend frequency stability (vs. temperature and battery voltage) to the implant’s transmitted signal. Reactance modulation would provide the needed FSK.
- Interface with outlink and inlink antennas
- Finalize modular approach to physiologic experiment flexibility
- Begin plans for miniaturization and packaging

**Outlink Receiver**
- Add DAC’s for automatic outlink receiver Image Rejection Filter tuning and for AGC control by receiver microcontroller
- These additions will be made in conjunction with a different microcontroller having more I/O ports including two serial ports (such as Motorola MC68HC12 or Phillips P51XA)
Future: Needed from ARC Group

- ABTS interface specifications
- System Decisions:
  - Antennas
  - Receivers
  - Receiver Multiplexing
- Habitat/Glovebox/Centrifuge Test Fixture
- Identify 1 or 2 initial physiology experiments

**ABTS interface specifications**
- Local and/or PC control? PC-104?
- Volume, cc; Ambient temperature; Vibration, etc.?
- Power available?

**System Decisions**
- Antennas for Biotelemeter Outlink and Inlink
- Number of outlink receivers per habitat?
- RF Multiplexing required?

**Habitat / Glovebox / Centrifuge Test Fixture**
- Configuration of Habitat outlink receivers and inlink transmitter
- Separate receiver “boxes”?

**Identity One or Two Initial Physiology Experiments**
- To set a goal for an initial trial
- Type, number of biomedical signals
- Sequencing time per animal
- Where will all that data go?
**Inlink Transmitter**

- Improve design for communication in Habitat (increase power?)

**Inlink Receiver**

- Sensitivity improvements depend largely on design of biotelemeter and Habitat antennas and inlink transmitter power. Communication software improvements in the implant's software will continue.