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Communications Technology for Unattended Sensors

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August, 1993

Lawrence
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Applied Technology Program (J Division)
Nonproliferation, Arms Controls, and International Security Directorate

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Abstract

Our objective was designing and demonstrating proof-of-concept communication subsystems for use in unattended sensors. These designs investigated current, advanced technology for frequency synthesis and control, and the use of commercial, highly integrated radio frequency components. The three following subsystems were evaluated: (1) a synthesized (225–400 MHz) exciter/transmitter, (2) a wideband, 100-W, radio-frequency power amplifier (for boosting the level of the exciter/transmitter output), and (3) and a command receiver operating in the 240–270-MHz satellite communication band. These subsystems were integrated into a prototype sensor system. Software was written using the Lawrence Livermore National Laboratory's Modular Intelligent Sensor System (MISS) specification for microprocessor control of these communication elements. Operation of the sensor system using these subsystems was demonstrated.

Introduction

Our objective was designing and demonstrating proof-of-concept (POC) communication subsystems for use in unattended sensors. These designs demonstrated the use of both advanced technology for frequency synthesis and control, and highly integrated commercial radio-frequency (rf) components. Three subsystems were designed and fabricated. Software enhancements were written and appended to existing control software to demonstrate an advanced, prototype sensor system.

The first step in this effort was generating a suitable set of specifications. The primary rationale for these specifications is that they represent nominal ranges of parameters useful in unattended-sensor designs. Secondary objectives included demonstrating a capability for future needs and attaining the packaging volumes.

The subsystems selected for development included an exciter/transmitter, a medium-power amplifier, and a command receiver. The exciter/transmitter provides a synthesized rf signal source that can be FSK-modulated. The frequency range is 225–400 MHz with frequency selection in 5-kHz increments. The power amplifier boosts the level of this rf signal to 100 W. The command receiver operates in the 240–270-MHz satellite communication band.

Remote Sensor Unit's Exciter/Transmitter Design

The design of the poc exciter/transmitter incorporated a number of innovations. A number of design concepts were evident in generating the specifications. These include—frequency synthesis for carrier frequency generation; linear FM (FSK with binary data) with a signal bandwidth of 25 kHz; digitally programmable; synthesizer output port for a receiver local oscillator. **Figure 1** is a block diagram of a concept exciter/transmitter; the initial specifications are given in **Table 1**.

A contract was placed with DSI* for the design of a synthesized exciter/transmitter conforming to these specifications. The block diagram of the DSI transmitter and a photograph of the physical unit are shown in **Figs. 2** and **3**. The unit generally conforms to the specifications (the exception being the power requirement at high temperature). Supporting technical data are provided in **Appendix A**.

*Defense Systems, Inc., 1521 Westbranch Drive, McLean, VA 201021

6-S/1319-01

Figure 1. Block diagram of a conceptual miniature synthesized exciter/transmitter.

Table 1. Specifications for miniature synthesized exciter/transmitter (as provided to vendor as part of purchase order).

frequency	225–400 MHz
frequency step size	5 kHz
frequency switching speed	10 ms nominal
frequency stability	±1 ppm over temperature
aging rate	<1 ppm/year for 2 years
synthesizer control	TTL levels
synthesizer output power level	10 dBm
modulation	FSK, 25-kHz wide, nominal
data rate	2400–9600 baud
data format	TTL levels
power output	0.1 W minimum into 50 ohms with 1.5:1 SWR
harmonic outputs	<–30 dBc
spurious outputs	<–80 dBc, at >20 kHz from carrier
phase noise	<–80 dBc/Hz at 10 kHz from carrier
dc power	5 V, 0.1 A max. in transmit, 20 mA max. in receive
transmitter duty cycle	5 sec on, 1 hr off using no external heat sink
humidity	95% max.
operating temperature range	–30 to +50°C
storage temperature range	–40 to +70°C
operating altitude	–100 to +7000 ft
size	4.25 x 2.5 x 1.5 in., max.
protection	thermal, SWR, over-voltage, and reverse polarity
MTBF	50,000 hr

6-S/1319-02

Figure 2. Block diagram of the DSI miniature synthesized exciter/transmitter.

Figure 3. *Photograph of the DSI miniature synthesized exciter/transmitter.*

Power Amplifier

The function of the power amplifier is boosting the signal level of the exciter/transmitter output. The specified gain is that required to supply the 100-W output with input from the exciter/transmitter.

Figure 4 is a block diagram of the power amplifier and specifications are listed in **Table 2**.

The amplifier component of the power amplifier was a standard component purchased from LCF* (**Fig. 5**).

The specified bandwidth, gain, and environmental characteristics of this unit meet system requirements. An additional lowpass filter on the output was required to meet the signal harmonic specification.

*LCF Enterprises, 651 Via Alondra, Unit 710, Camarillo, CA 93010

6-S/1319-04

Figure 4. Diagram of a conceptual power amplifier.

Table 2. Specifications for the LCF power amplifier (purchased item).

frequency	225–400 MHz, nominal
power output	100 W minimum into 50 ohms with <1.5 : 1 SWR and with 0.1 W input
harmonic outputs	<–30 dBc below 550 MHz <–35 dBc above 550 MHz when driven with signal of <–30 dBc harmonic content
dc power	24 to 30 Vdc, 9 A, maximum while transmitting, 0 A while in standby
transmitter duty cycle	5 sec on, 1 hr off using no external heat sink
humidity	95% max.
operating temperature range	–30 to +50°C
storage temperature range	–40 to +70°C
operating altitude	–100 to +7000 ft
size	4.85 x 2.5 x 1.5 in., max.
protection	thermal, SWR, over-voltage, and reverse polarity
MTBF	50,000 hr

Figure 5. Photograph of the LCF power amplifier

The amplifier has been tested for conformance with specifications for power output and gain at room temperature. Support precluded the evaluation over the full environmental range.

Note is that the LCF unit is specified for +28 Vdc; both gain and output power are reduced by about 15% when operated at 24 Vdc. LCF indicated that the design could be modified to meet the operational specifications at the lower supply voltage.

Amplifier output regulation and protection, and signal filters were designed by LLNL. In testing, the power-amplifier subsystem readily delivered 100 W of output power over the entire band with less than -40 dBc harmonic content.

Command Receiver

The command receiver provides an rf command and control link to the remote sensor unit. This application requires a receiver with the following design features:

- low power
- reasonably narrow bandwidth
- power control (to implement power saving)
- BPSK to achieve optimum performance in noise background

The receiver bandwidth, noise figure, and demodulation format were obtained from a trade-off analysis that considered such factors as the expected command-source signal levels (minimum with fluctuations and fading), receiver antenna gain and noise figures, required bit error rate (BER) and maximum data transmission rate, energy requirements, and operating time. Table 3 lists the set of specifications for the command receiver meeting these requirements.

A block diagram of the POC receiver is shown in Fig. 6. This design uses a local oscillator (supplied by the synthesized exciter/transmitter), an input amplifier and filter, an up-converter, an IF amplifier, and a BPSK demodulator and clock recovery circuit. The IF amplifier is an NCI

Table 3. Specifications for the command receiver.

frequency	240–270 MHz, nominal
frequency stability	±1 ppm over temperature range and over 2 years' aging
sensitivity	< 0.25 μ V for 10^{-5} BER
adjacent channel selectivity	70 dB @ ± 5 kHz
spurious responses	70 dB
intermodulation immunity	60 dB at reference sensitivity
modulation	BPSK, 100 bps, TTL output
receiver bandwidth	1 kHz
phase noise	<–80 dBc/Hz at 10 kHz
dc power	5 V, 20 mA
humidity	95% max.
operating temperature range	–30 to +50°C
storage temperature range	–40 to +70°C
operating altitude	–100 to +7000 ft
size	4.25 x 2.5 x 1.0 in.
protection	over-voltage, and reverse polarity
MTBF	50,000 hr

Systems receiver, model NCD1003*; it operates at a 400-MHz center frequency. The up-converter translates the 240–270-MHz satellite communications downlink band to the IF frequency. The LLNL-designed BPSK demodulator and clock recovery recovers the message bitstream and transfers these data into the microcontroller. This developmental receiver is packages in a utility enclosure, shown in Fig. 7.

The receiver sensitivity has been measured at 0.3 mV. Assuming receiver noise to the limiting system factor, a BER of 10^{-5} over the MHz band should be supported. Tests characterizing the receiver were limited to sensitivity, noise, measurement of the passband, and power requirements. This characterization indicated that the receiver noise is about 6 dB greater than the design goal of C/N of 0 dB.

Figure 6. Diagram of the proof-of-concept command receiver.

*NCI Systems, E. 49th Midland Avenue, Paramus, NJ 07652

Figure 7. *Photograph of the proof-of-concept command receiver.*

Appendix A. Exciter/transmitter Test Data*

A block diagram of the exciter/transmitter is shown by Fig. A-1. This design is based around a band-switched, voltage-controlled oscillator (VCO); the VCO schematic is given in Fig. A-2. The VCO operates in two ranges—225.000–300.00 MHz and 300.005–400.000 MHz. The VCO output is lowpass-filtered to reduce the harmonic signals. The filtered rf signal is steered to one of two outputs: a +10 dBm receiver local oscillator reference, or a +20 dBm transmitter output. The output transmitter power and the required supply current over the specified range of frequency and temperature (range of -20 to +50°C) are given in Figs. A-3 through A-8. The measured spectrum of the output is shown in Figs. A-9 and A-10; these data were taken at +50°C and -30°C, respectively.

The VCO is frequency-modulated (linear FM/FSK) by controlling the loop error voltage with the information signal. The nominal modulation sensitivity results in a 25-kHz frequency deviation (± 12.5 kHz) about the carrier frequency. The loop gain (sensitivity) changes as the VCO frequency is varied (by changing the feedback counter ratio). Thus, the level of the modulation signal must be varied to maintain the 25-kHz carrier deviation. The gain variation required to maintain the carrier deviation is illustrated in Fig. A-11.

The VCO loop bandwidth also sets a lower data rate (frequency) limit for the modulation signal. Figures A-12 through A-17 illustrate the phase shift in a 40-Hz square wave at various rf carrier frequencies.

The programming sequence for the VCO is defined in Fig. A-18. A communications interface was designed to adapt this interface to the MISS bus. A block diagram of the interface is shown in Fig. A-19 and is illustrated in Fig. A-20. Figure A-21 shows the test setup ("breadboard").

*These experimental data were provided by the contractor, Defense Systmes Inc.,
1521 Westbranch Drive, McLean, Va 220102

6-S/1319-A1

Figure A-1. Diagram of the DSI miniature synthesized exciter/transmitter loop block diagram.

Loop phase margin = 45 degrees
 Loop natural frequency = 50 Hz
 Loop time constant = 0.02 sec

6-S/1319-A2

Figure A-2. Synthesizer-loop block diagram.

6-S/1319-A3

Figure A-3. Output power as a function of frequency at +25°C..

6-S/1319-A4

Figure A-4. Output power as a function of frequency at +50°C..

6-S/1319-A5

Figure A-5. Output power as a function of frequency at -30°C .

6-S/1319-A6

Figure A-6. Supply current as a function of frequency at $+25^{\circ}\text{C}$.

6-S/1319-A7

Figure A-7. Supply current as a function of frequency at +50°C.

6-S/1319-A8

Figure A-8. Supply current as a function of frequency at -30°C.

6-S/1319-A9

Figure A-9. Phase noise spectrum,
100 kHz about 400 MHz at +50°C.

6-S/1319-A10

Figure A-10. Phase noise spectrum,
100 kHz about 400 MHz at $\pm 30^\circ\text{C}$.

6-S/1319-A11

Figure A-11. Modulation amplitude control gain for constant 25-kHz frequency deviation.

Figure A-12. Demodulated exciter/
transmitter output, 40 Hz modulation, 225
MHz center frequency.

Figure A-13. Demodulated exciter/
transmitter output, 40 Hz modulation,
250 MHz center frequency.

Figure A-14. Demodulated exciter/
transmitter output, 40 Hz modulation,
300 MHz center frequency.

Figure A-15. Demodulated exciter/
transmitter output, 40 Hz modulation,
301 MHz center frequency.

Figure A-16. Demodulated exciter/
transmitter output, 40 Hz modulation,
350 MHz center frequency.

Figure A-17. Demodulated exciter
transmitter output, 40 Hz modulation,
400 Hz modulation, center frequency.

The A register need only be loaded on the first programming.
TX key enables 100-mW output when high, 10-mW output when low.
TX data is NRZ data preferably with no spectral components below 200 Hz.
Out-of-lock (OOL) pin is low when the synthesizer is locked.
All pins are HCMOS compatible.

6-S/1319-A18

Figure A-18. Synthesizer programming sequence.

6-S/1319-A19

Figure A-19. Block diagram of MISS bus communication interface.

Figure A-20. Photograph of the MISS bus communication interface.

Figure A-21. Photograph of the MISS bus communication breadboard.

Appendix B. Power Amplifier Test Data

LCF ENTERPRISES
RF Power Amplifiers
621 Barrington Court
Newbury Park, CA 91320-5117
(805) 388-8454

Test Data
A020 Serial No. 02A

V_d : 28 V maximum power-supply voltage
 V_g : 15.0 V MAXIMUM GATE VOLTAGE
 I_{dq} : 100 mA per side stage 1
0.2 A per side stage 2
0.2 A per side stage 3

Temperature: 25°C
8/29/92
Tested by PFF (with external resistors)

WARNING! WARNING! WARNING! WARNING! WARNING! WARNING!

This is a high-performance unit in a very small package. Please read the included application note on high performance, open-architecture amplifiers. If you have any questions, please contact LCF technical support.

Maximum recommended RF input drive: 17 dBm (50.12 mW)
Maximum recommended RF output: 50.21 dBm (105 W) INTO 50 OHM NOMINAL LOAD
Maximum recommended drain current: 5.0 A per side

HEAT SINK REQUIRED. USE THERMAL COMPOUND.

MAXIMUM RECOMMENDED CASE TEMPERATURE FOR FULL RATED OUTPUT POWER IS 60°C.

RECOMMEND USING TWO SEPARATE FAST BLOW FUSES OF 5.0 AMP PER SIDE FOR INITIAL TURN ON AND SET UP.

BE CAREFUL NOT TO EXCEED THE MAXIMUM OUTPUT POWER DUE TO GAIN VARIATION ACROSS THE BAND. AN INPUT DRIVE LEVEL CORRESPONDING TO THE RATED OUTPUT POWER AT THE LOWER GAIN PORTIONS OF THE BAND WILL OVERDRIVE THE AMPLIFIER IN THE HIGHER GAIN PORTIONS OF THE BAND.

THE POWER RATING APPLIES TO A 50-OHM NOMINAL LOAD. DO NOT DRIVE FULL POWER INTO A BAD MISMATCH.

Note: Power-supply surges can result from abrupt changes in load current. DO NOT PULSE FULL RF INPUT DRIVE OFF TO AVOID AMPLIFIER BURNOUT. That is, many power supplies cannot respond to a current change of approximately 10 A through the lead inductance in a few microseconds, and pulsing the RF drive off abruptly can deliver a large voltage spike at the amplifier depending on the power supply connection. Either adjust RF input drive up and down gradually, or turn off power supply before abruptly turning full RF input drive off. A large electrolytic capacitor connected *directly* to the amplifier output stage power supply feedthru will help filter power supply surges.

Note: Low-frequency feedback between stages through the power supply connection can generate low-frequency oscillations in the power supply lines which can develop breakdown voltage on the transistors. ENSURE THERE IS GOOD LOW-FREQUENCY ISOLATION AND DECOUPLING IN THE POWER SUPPLY CONNECTION BETWEEN THE STAGES TO AVOID AMPLIFIER BURNOUT.

Table B-1. Specifications for miniature synthesized exciter/transmitter

Freq	Output Power	Drain Voltage	Drain Current	DC Power	Eff	Gain
400 MHz	101.1 W	28.37 V	I1 4.35A I2 4.27A	244.6 W	41.3%	37.5 dB (+12.5 dBm in)**
380 MHz	100.9 W	28.49 V	I1 4.21A I2 4.07A	235.9 W	42.8%	35.0 dB (+15.0 dBm in)
360 MHz	100.1 W	28.59 V	I1 4.71A I2 4.48A	262.7 W	38.1%	33.5 dB (+16.5 dBm in)
340 MHz	101.0 W	28.70 V	I1 4.42A I2 4.45A	254.6 W	39.7%	34.8 dB (+15.2 dBm in)
320 MHz	101.5 W	28.79 V	I1 4.91A I2 4.92A	283.0 W	35.9%	35.0 dB (+15.1 dBm in)
300 MHz	100.7 W	27.79 V	I1 4.57A I2 4.55A	253.4 W	39.7%	36.5 dB (+13.5 dBm in)
280 MHz	101.7 W	27.85 V	I1 4.54A I2 4.52A	252.3 W	40.3%	37.5 dB (+12.6 dBm in)
260 MHz	101.8 W	27.93 V	I1 4.39A I2 4.38A	245.0 W	41.6%	39.1 dB (+11.0 dBm in)
240 MHz	102.5 W	28.08 V	I1 4.14A I2 4.15A	232.8 W	44.0%	39.2 dB (+10.9 dBm in)
220 MHz	103.0 W	28.17 V	I1 3.97A I2 4.05A	225.9 W	45.6%	38.1 dB (+12 dBm in)

** Input power level

END

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