UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
WASHINGTON, DC 20207

Memorandum

Date: MAR 23 2004

TO	:	The Commission Todd A. Stevenson, Secretary
THROUGH	:	W. H. DuRoss, III, General Counsel Patricia Semple, Executive Director
FROM	:	Jacqueline Elder, Assistant Executive Director Office of Hazard Identification and Reduction Arthur S. Lee, Electrical Engineer Directorate for Engineering Sciences
SUBJECT	:	Contractor Report on *The Implementation and Demonstration of Wireless Communications Capabilities in Off-the-Shelf, Battery-Powered Smoke Alarms Phase II Report*

Attached is a report on the second phase of a study to demonstrate wireless interconnect technology for battery-operated smoke alarms. This report was completed by the Naval Research Laboratory (NRL) under contract to the U.S. Consumer Product Safety Commission (CPSC). An earlier report by NRL, *Smoke Alarms, Low Cost Batteries and Wireless Technology Technical Report and Literature Search*, examined the feasibility of incorporating wireless technology into battery-operated smoke alarms.

For the second phase of the study, NRL modified commercially available residential smoke alarms to incorporate a wireless technology; several prototypes were built to demonstrate the concept. The attached report provides details regarding prototype construction, the technology used, and demonstration results. The NRL report also provides cost information for the parts used in building transmitter and receiver circuit boards for their designs.

Interconnection of smoke alarms can result in increased egress time for occupants by sounding all alarms when smoke is detected at the furthest part of the home. The CPSC staff believes that incorporating wireless interconnection in battery-operated smoke alarms can reduce fire deaths. Options for future work include:

- Cost benefit analysis
- Engineering evaluation to compare occupant notification times associated with interconnected alarms and non-interconnected alarms
- Engineering analysis to quantify the notification time for a wireless smoke alarm system that includes potential early warning devices, such as remote fire detection modules, if placed in appliances or high-risk fire areas

- Examination of legislation and supporting data used by states and local jurisdictions to pass legislation requiring interconnected smoke alarms.

These additional activities may be used to support future recommendations for changes to the voluntary standard and/or the Life Safety Code (NFPA 101).

Attached:
The Implementation and Demonstration of Wireless Communications Capabilities in Off-the-Shelf, Battery-Powered Smoke Alarms Phase II Report

Naval Research Laboratory
Washington, DC 20375-5320

NRL/MR/6180--04-8712

The Implementation and Demonstration of Wireless Communications Capabilities in Off-the-Shelf, Battery Powered Smoke Alarms Phase II Report

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REPORT FOR

United States Consumer Product Safety Commission
Lanham, MD

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13. SUPPLEMENTARY NOTES

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14. ABSTRACT

This report details the development, implementation, and demonstration of wireless communications capabilities in modified, battery powered commercial smoke alarms. Power consumption concerns are addressed due to the necessity of achieving extended operation using battery power for the smoke alarm and the communication circuitry. Communications designs and the costs of implementing these designs are explained in detail.

15. SUBJECT TERMS

Smoke alarms; RF communications; Wireless technologies; Sonic communications; Battery power; Wireless Communications; Batteries

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The Implementation and Demonstration of Wireless Communications Capabilities In Off-The-Shelf, Battery Powered Smoke Alarms Phase II Report

1.0 INTRODUCTION

In 1974 in excess of 8000 Americans were dying in fires annually, 80% of them in residential fires. In 1974, the report of the presidential commission on fire, *America Burning*, recommended that Americans protect themselves from fire at home by installing smoke detectors. The building codes of the time applied the same requirements on residential dwellings that were used in commercial buildings. Thus, a homeowner wanting a code compliant home fire alarm system had to install a heat detector in every room and one smoke detector, all connected to a control panel. The expense of installing this code compliant system prevented it from being widely utilized. Later, experiments known as the Indiana Dunes Tests were conducted on actual homes scheduled for demolition to evaluate ionization and photoelectric smoke detectors and residential heat detectors being sold at the time. The Indiana Dunes Tests found that smoke alarms located outside bedrooms and on each additional story including the basement provided adequate escape time for most residential fires. Building codes were soon revised to require every level protection in both new and existing homes. In recent years, the National Fire Protection Association (NFPA) has required all smoke alarms in new constructions to be interconnected. The interconnected smoke alarms allow all the smoke alarms to sound if any individual alarm detects smoke. This allows an increase in escape time and life protection for occupants. This requirement was only applicable to smoke alarms powered by 120 VAC or house wiring. A large number of homes were constructed before smoke alarms were required and battery powered smoke alarms were installed later. These battery powered smoke alarms are not capable of supporting the NFPA interconnection requirement because they were not designed to be interconnected. Current wireless technology can support a communication link between individual battery powered smoke alarms allowing all smoke alarms to sound if any single smoke alarm detects smoke.

The U.S. Consumer Product Safety Commission sponsored a technology study [1] to determine if any current wireless technology was suitable to implement a wireless communications link that would allow battery powered smoke alarms to communicate alarm conditions between one another as if they were hardwired without significantly increasing manufacturing costs or prematurely depleting the life of a standard 9-volt battery. The study found several wireless technologies capable of supporting a wireless communication link between smoke alarms without degrading the smoke alarm's performance or prematurely depleting the battery power source. The technology study recommended implementing two wireless communications technologies: Radio Frequency (RF) and Sonic. Details of the implementation of these two approaches are presented here.

Manuscript approved January 15, 2004.

2.0 WIRELESS COMMUNICATION DESIGN REQUIREMENTS AND LIMITATIONS

The objective of this work is to demonstrate that wireless technologies can be incorporated into battery operated smoke alarms without drastically increasing the cost of the smoke alarm, retaining the primary power source, not increasing the general size of the smoke alarm and providing a reliable interconnection between smoke alarms without false alarming. The wireless technology selected must also meet the following criteria;

- If a secondary battery is used, it must be of reasonable size to be able to fit inside a smoke alarm housing and last for at least 10 years,
- The primary battery source must still be able to pass the battery test in *UL 217 Single and Multiple Station Smoke Alarms, Section 63,*
- Be able to communicate through typical residential walls and floors,
- Be unique code selectable,
- Not nuisance alarm,
- Have low interference with other wireless communication and/or building structure, and
- Consume low power.

A successful implementation of any wireless communication link to demonstrate a particular wireless technology will incorporate as much of the above design criteria as is feasible or cost effective as long as any deficiency is correctable in future implementations, and the solution is supported by adequate design background.

3.0 THE RADIO FREQUENCY (RF) COMMUNICATION SMOKE ALARM PROTOTYPE

A commercial smoke alarm was modified to incorporate an RF transmitter and receiver capable of transmitting and receiving alarm conditions between battery powered smoke alarms within a residence or structure. The RF transmitter is used to transmit alarm conditions detected by this smoke alarm to other smoke alarms within range of the transmitted signal, forcing the receive units into an alarm condition and sounding their alarm horns. The RF receiver is designed to receive alarm conditions detected by other smoke alarms within range of the receiver and force this smoke alarm into an alarm condition and sound the unit's alarm horn. A system consisting of these modified smoke alarms covering a residence would sound all of the system's smoke alarm horns when one smoke alarm in the system detects smoke. A properly designed and installed system could provide excellent coverage within a residence or structure and could be as effective as a hardwired interconnected system.

3.1 Explanation of Implemented RF Communication Design

The circuitry for the RF implementation of the wireless smoke detector is based on a transmitter/receiver chipset by Micrel Semiconductor Inc. The MICRF series IC's are intended for low-cost, unlicensed, wireless applications such as Remote Keyless Entry Systems, Remote Fan/Light Controls, Garage Door Openers, and Remote Sensor Data Links such as those used for home security systems. The IC's are usable at frequencies from 300 MHz to 470 MHz. An operating frequency of 433.92 MHz was used for this application. A relatively high frequency was chosen to minimize antenna length for the receive quarter-wave monopole. If a longer antenna proves practical, for example, by inserting the receive antenna wire into a hole in the wall behind the detector, lower frequencies, around 300 MHz, may be more omni-directional and have less path loss caused by intervening objects. The present application uses an encoder/decoder chipset by Holtek Semiconductor Inc., their HT12 series, to assign a unique code for smoke detector operating sets. This chipset is not encrypted and was chosen for the prototypes to simplify debugging. If an encrypted code sequence is desired for a consumer product, an encrypted chipset such as the Keelog series by Microchip Technology Inc. will be more appropriate.

A. RF Transmitter

The RF transmitter, Figure 1, uses a Micrel MICRF102BM for U1 operating at 433.92 MHz. U1 differentially drives a loop antenna, which is made as a track on the PC board. Capacitors C6 and C8 are the tuning for the 50 nH nominal antenna inductance. The MICRF102BM has automatic antenna tuning internally, so no external trimming is necessary to compensate for board-to-board antenna inductance variance. The crystal Y1 is chosen for the 433.92 MHz operating frequency. The MICRF102BM has an internal frequency multiplier to allow inexpensive low-frequency crystals to be used. The 13.56 MHz crystal frequency is multiplied by 32 to obtain the output at 433.92 MHz. R11/R12/C4 set the output power to a level consistent with Federal Communications Commission (FCC) regulations on unlicensed radiators. C1/C2/C3 are power supply bypass capacitors. For operation with an existing smoke alarm, a peak detector consisting of Q3 and C5 captures a high level from a point in the smoke alarm that pulses during alarm conditions. Q2 is switched ON through R17 by the output of the peak detector and, in turn, switches Q1 ON through R15. Q1 applies 9 VDC power to the 5 VDC regulator IC U3. U2 is a Holtek HT12E 2^12 encoder. Dip switches SW1, SW2 and SW3 program the bit pattern of U2. The data of U2 is used to ON-OFF key (OOK) modulate U1.

B. RF Receiver

The RF receiver, Figure 2, uses a Micrel MICRF007BM for U1 operating at 433.92 MHz. At J3, a quarter-wave length of wire is attached for an antenna. Y1 is the tuning crystal for the local oscillator of U1. The 6.7458 MHz is multiplied by 64.5 times inside U1. C5 sets the automatic gain control (AGC) time constant for U1. C6 averages the demodulated data to establish a slicing level for the internal data comparator. C1/C2/C3/C4 are power supply bypass capacitors used to clean up the power source. Q2 can be switched ON through R17 by placing a positive voltage at J4 pin 1, or J2 pin 1 may be grounded which switches Q1 ON through R15. Q1 applies 9 VDC power to the 5 VDC regulator IC U3. U2 is a Holtek 2^12 Decoder. The received data from U1 is applied to U2, which is enabled if the data pattern received matches that chosen by the dip switches SW1, SW2 and SW3. If U2 is enabled, Q3 is switched ON through R14. Q4 is then switched ON to short the pins of J5. J5 is connected across the TEST switch of the smoke alarm, so the alarm can be enabled.

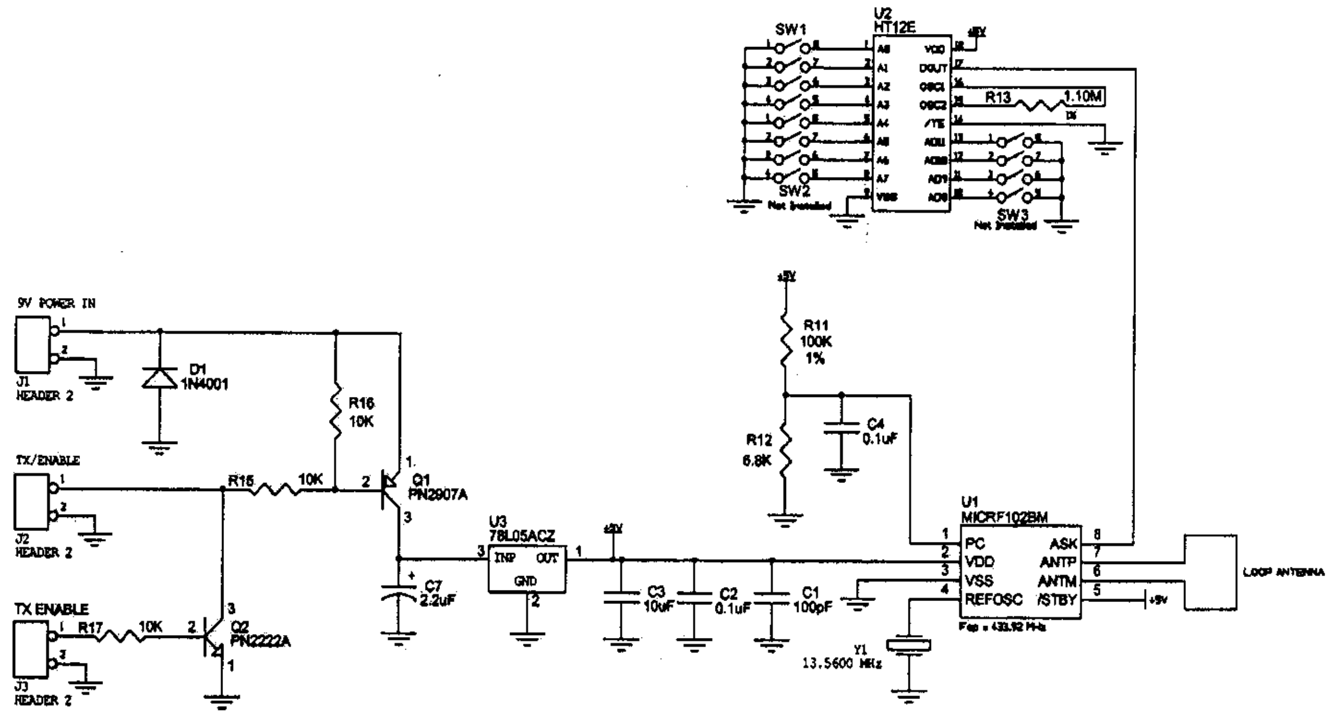

FIGURE 1. RF_TX. VERSION 1

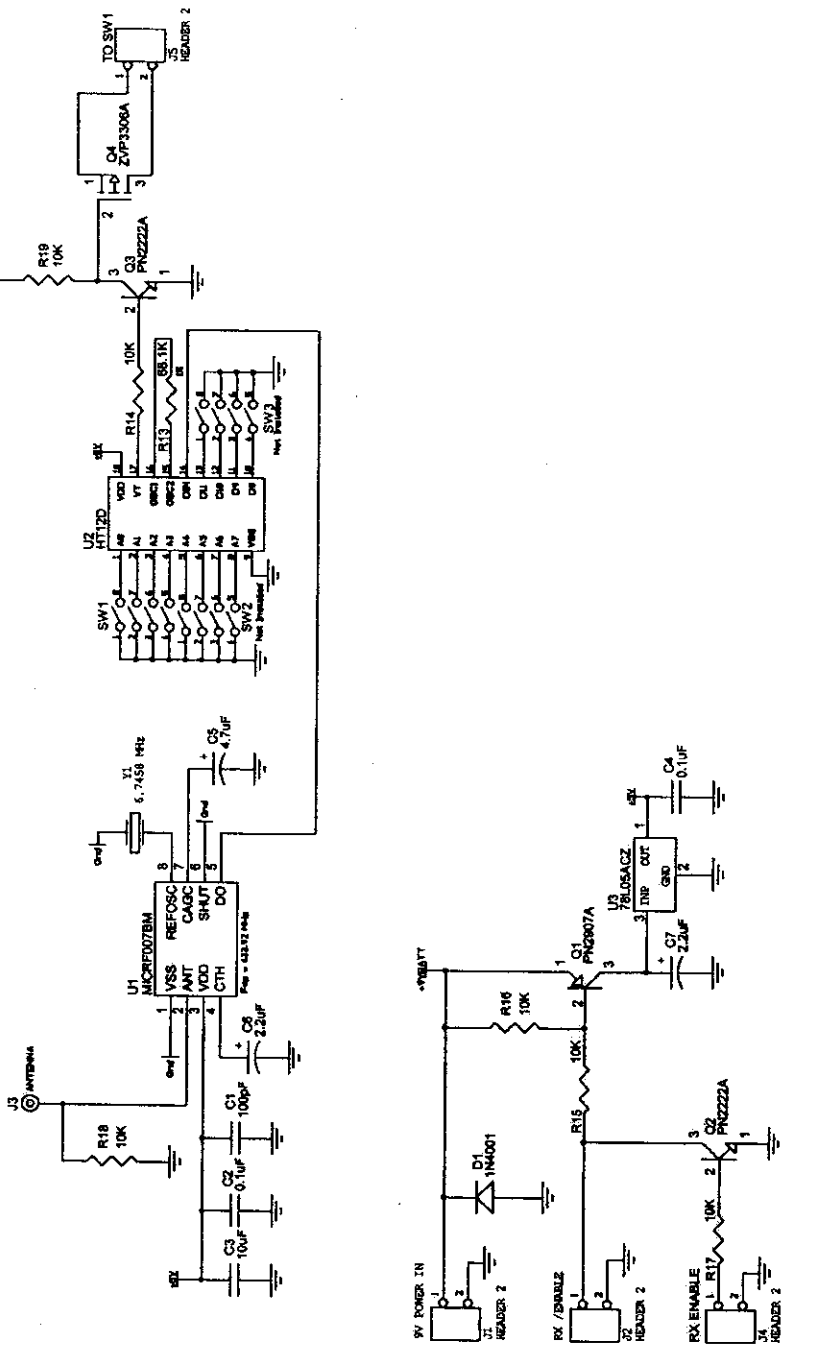

FIGURE 2. RF_RX

3.2 RF Experimental Results

The RF version of the wireless smoke detector has been built and tested. The RF receiver was implemented and tested with no revisions to the design, and the RF transmitter was implemented and tested with minor design changes that were implemented in one revision to the original design. The 300 – 470 MHz Wireless Transmitter (version 1) used a track on the PC board that went all the way around the edges of the circuit board to form the antenna. This antenna implementation failed to allow a full allowable power level to be transmitted from this PC board. Also, the height of crystal Y1 interrupted the antenna pattern and reduced the effectiveness of this application of the transmitter. Version 2 of the 300 – 470 MHz Wireless Transmitter, Figure 3, corrected the version1 deficiencies by employing a compact Y1 crystal, moving components away from the area where the antenna track was located and by redesigning the antenna track as per the Micrel demonstration board design for the antenna and chipset. C6 and C8 were added in this implementation to tune the antenna for maximum power transfer.

4.0 THE SONIC COMMUNICATION SMOKE ALARM PROTOTYPES

Two versions of the sonic transmitter/receiver design were implemented. The first receiver/transmitter combination was the "Wireless Smoke Detector Sonic Tx" and the "Wireless Smoke Detector Sonic Rx." This combination uses ON/OFF Keying (OOK) to modulate the alarm horn and would be the simplest design to implement because of the reduced component count and the reduced design complexity. The second receiver/transmitter combination was the "Wireless Smoke Detector FM Sonic Tx" and the "Wireless Smoke Detector FM Sonic Rx." This combination uses a two-tone frequency shift keying (FSK) modulation implementation. This design is more robust and more complex to implement using an FM IF System to decode the FSK signal. Each tone is generated using RC time constants to generate the frequencies. A "1" is represented by the transmission of the higher frequency and a "0" is represented by the transmission of the lower frequency.

In order to simplify the implementation of the sonic approach, use of components such as the alarm horn installed in the smoke alarms was anticipated. Each of the two sonic implementations was adversely affected due to the use of standard smoke alarm components. In the ON/OFF Keying case, the standard alarm horn, which is normally used in a steady state when it is activated, did not respond well to being turned on and off to modulate the code sequence information. It was felt that a two-frequency alarm horn, speaker or ceramic transducer might respond more favorably to a change in frequency rather than to an abrupt turning ON and OFF. Therefore, the FM version of the sonic approach was implemented. The alarm horn was replaced by a speaker in this implementation. The FM sonic receiver uses an omni-directional microphone as the receive sensor to detect the modulated tone from the sonic transmitter because the use of a standard microphone in this application would cause directional reception qualities not desirable here. Further research should overcome the shortcomings of the current implementations and provide another wireless alternative for this effort.

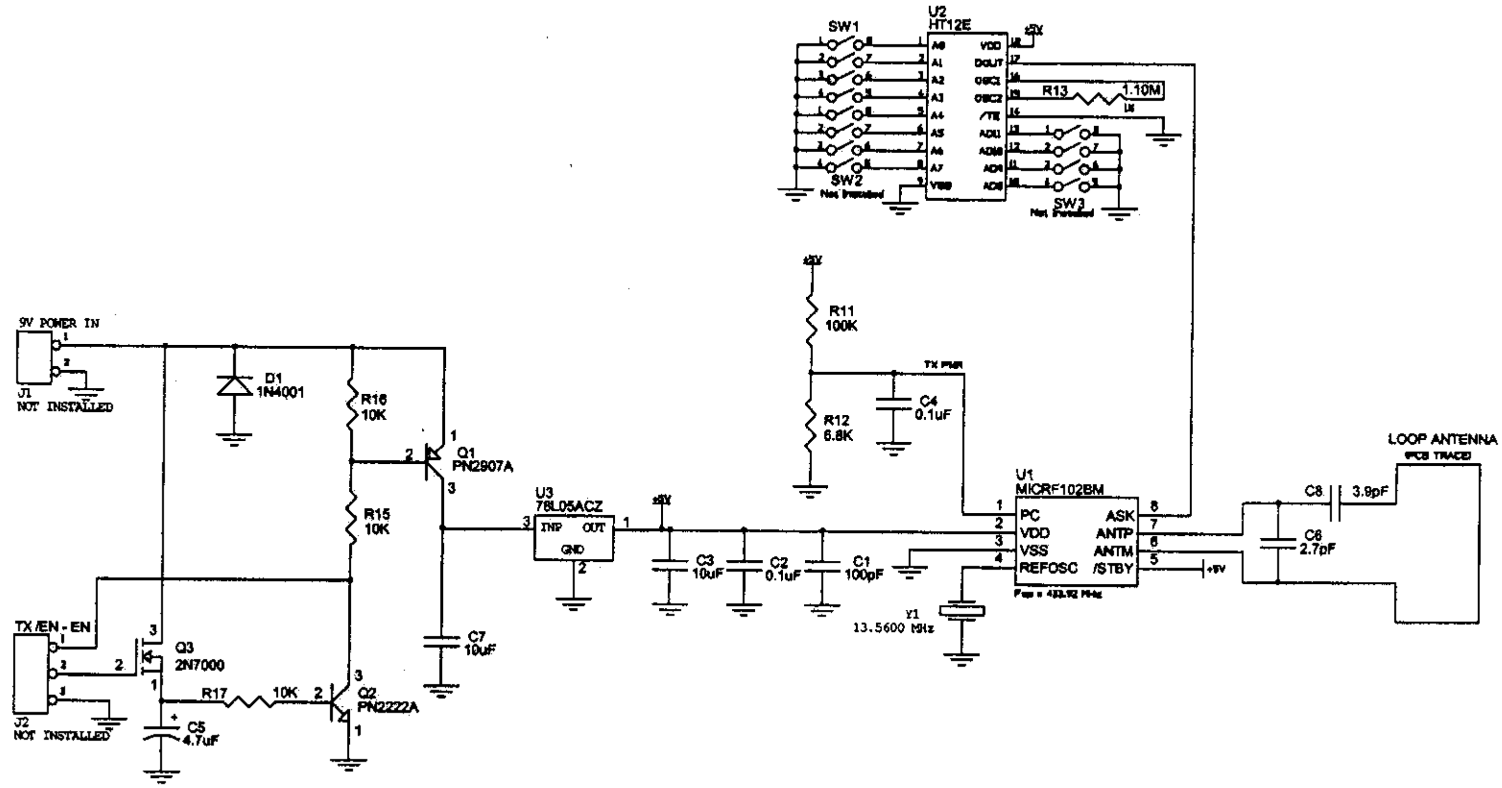

FIGURE 3. RF_TX, VERSION 2

(Revised Loop Antenna)

4.1 Explanation of Implemented Sonic Communication Design

Two different sonic designs of the wireless smoke detector were implemented. One design was based on ON/OFF Keying (OOK), a form of Amplitude Modulation (AM), and the other design was based on Frequency Shift Keying (FSK), a form of Frequency Modulation (FM). Both types modulated the alarm horn at the transmitter end using a unique binary encoding, and both types demodulated the signal at the receiver end to recover the unique binary code and sound the alarm horn if the code matched.

4.1.1 OOK AM Sonic Implementation

The AM sonic implementation of the wireless smoke detector, originally called the sonic implementation, is based on ON/OFF Key Amplitude Modulating the alarm horn at the transmitter using a unique binary encoding. The amplitude-modulated alarm is received, processed and decoded at the receiver end. The transmitter consists of an oscillator at 4 KHz that is keyed ON and OFF in response to a binary data stream generated by an encoder. The output of the oscillator drives the alarm horn. The receiver begins with a microphone followed by bandpass filters. The bandpassed frequencies are input to a tone decoder IC, which responds to tones that are within its selected range of frequencies. The output of the tone decoder is demodulated data that is input to a tone decoder. If the decoder has received an appropriate data pattern, the smoke alarm at the receiver end is sounded.

The encoder and decoder are implemented using a chipset by Holtek, their HT12 series, to assign a unique code for both smoke detector operating sets. This chipset is not encrypted and was chosen for the prototypes to simplify debugging. If an encrypted code sequence is desired for a consumer product, an encrypted chipset such as the Keeloq series by Microchip Technology Inc. will be more appropriate.

A. (AM) Sonic Transmitter

The AM Sonic Transmitter design is shown in Figure 4. Stepping through its design, U1 is an LMC555CN Timer IC connected as an astable multivibrator with frequency determined by R14 and C3. Its output is a 0 – 9VDC square wave at 4 KHz when it is switched on. The output of U1 is connected to one end of a piezo buzzer SPK1 and is input to U4. U4 is another LMC555CN. U4 inverts the phase of the U1 signal and drives the other end of SPK1. Driving SPK1 in this way doubles the drive voltage for greater alarm output. U2 is a Holtek HT12E 2^12 encoder. Dip switches SW1 and SW2 program the bit pattern of U2. The data from U2 is used to switch Q2 ON and OFF. Q2 switches the negative power supply to U1 and U4, keying them ON and OFF in response to the data stream. For operation with an existing smoke detector, a peak detector consisting of Q4 and C5 captures a high level from a point in the smoke alarm, which pulses during alarm conditions. Q3 is switched ON through R17 by the output of the peak detector and, in turn, switches Q1 on through R15. Q1 applies 9 VDC power to U2. C2/C4/C7 are power supply bypass capacitors.

B. (AM) Sonic Receiver

The AM Sonic Receiver design is shown in Figure 5. Stepping through its design, MIC1 is an Electret Microphone to receive the transmitted alarm signal. The signal from MIC1 goes to the bandpass filters at U3 and U2 and their surrounding resistors and capacitors. Signals within about 200 Hz of 4 KHz are amplified and input to U1, a tone decoder. U1 is set to respond to 4 KHz by the values of R15 and C11. C9 and C10 determine the range of frequencies accepted by U1. Q5 inverts the data from U1 and applies it to U7. U7 is a Holtek 2^12 decoder. U7 is enabled if the data pattern received matches that are chosen by the dip switches SW1 and SW2. If U7 is enabled, Q3 is switched ON through R21. Q4 is then switched ON to short the pins of J5. J5 is connected across the test switch of the smoke detector, so the alarm is enabled.

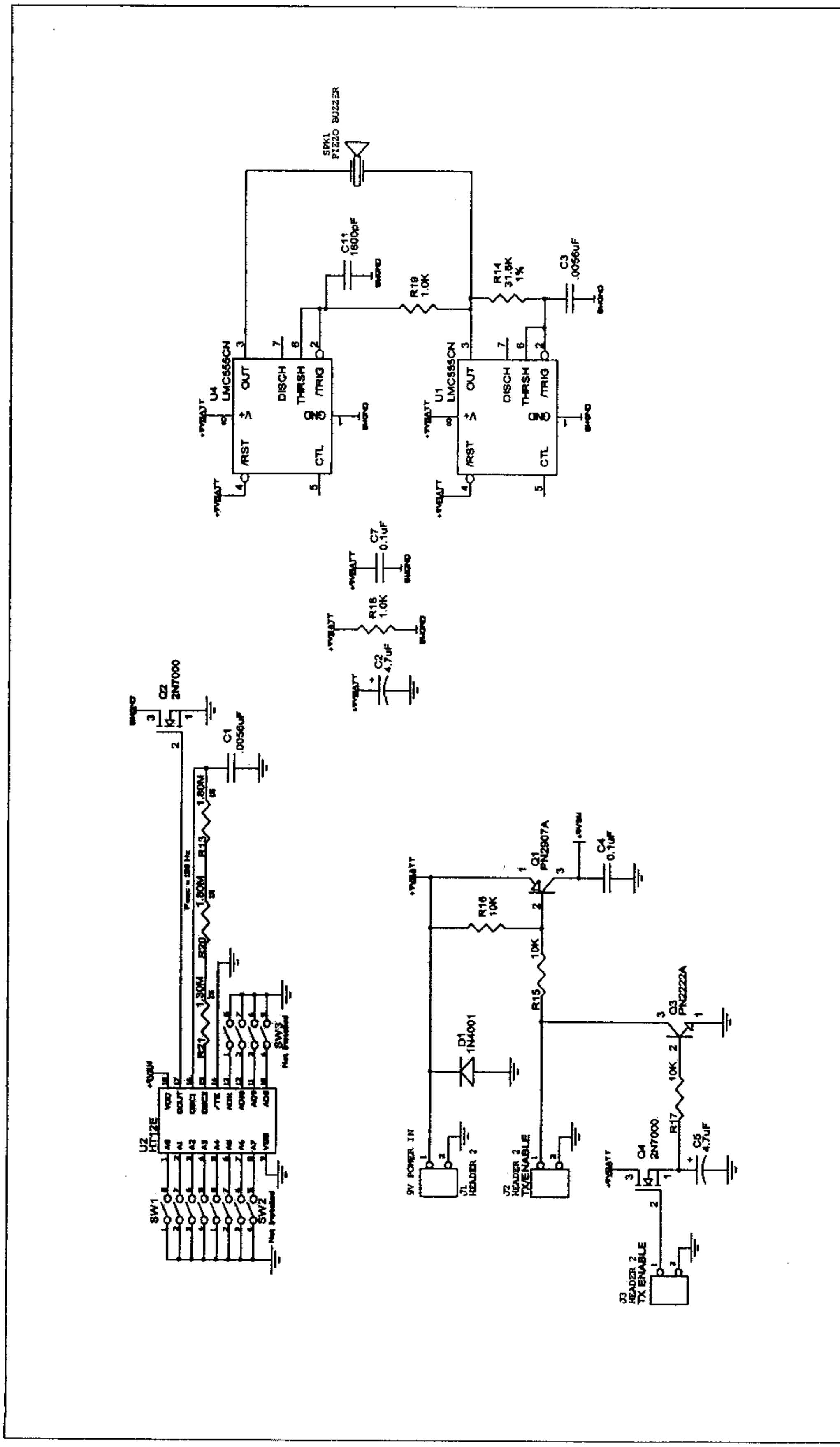

FIGURE 4. SONIC_TX_AM

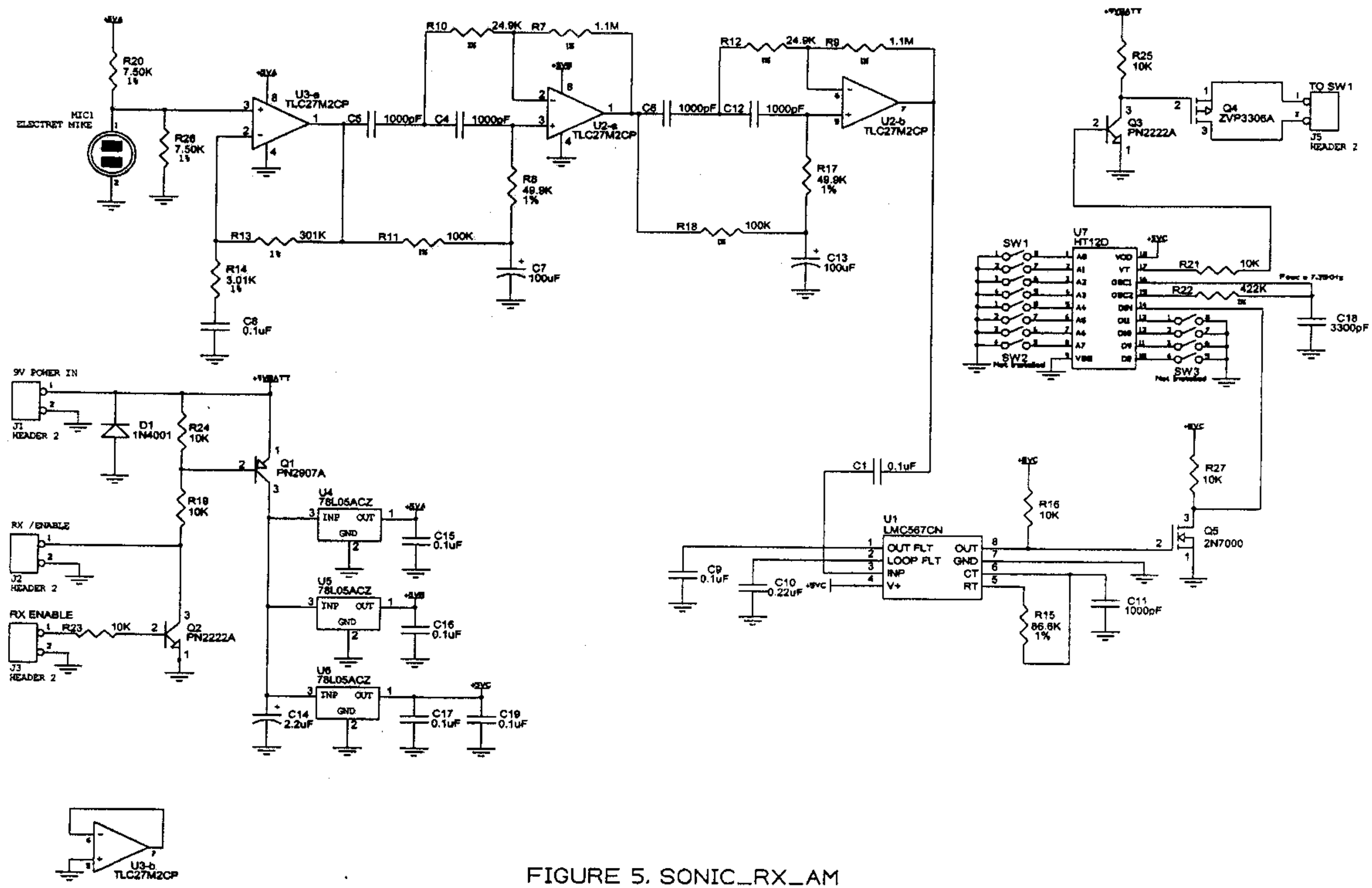

FIGURE 5. SONIC_RX_AM

4.1.2 FSK FM Sonic Implementation

The FM Sonic implementation of the wireless smoke detector is based on Frequency Shift Key (FSK) frequency modulating the alarm horn at the transmitter end using a unique binary encoding. The frequency-modulated alarm is received, processed and decoded at the receiver end. The transmitter consists of an oscillator that is keyed back and forth between 3.6 KHz and 3.8 KHz in response to a binary data stream generated by an encoder. The output of the oscillator drives the alarm horn. The receiver begins with a microphone followed by bandpass filters. The bandpassed frequencies are input to an FM IF System IC, which has two limiting amplifiers to suppress AM modulation, and a quadrature detector. The output of the quadrature detector is demodulated data; it is filtered, sliced and input to a decoder. If the decoder has received an appropriate data pattern, the smoke detector alarm at the receiver end is sounded.

The present application uses an encoder/decoder chipset by Holtek, their HT12 series, to assign a unique code for smoke detector operating sets. This chipset is not encrypted and was chosen for the prototypes to simplify debugging. If an encrypted code sequence is desired for a consumer product an encrypted chipset such as the Keeloq [series by Microchip Technology Inc. will be more appropriate.

A. FM Sonic Transmitter

The FM Sonic Transmitter design is shown in Figure 6. U1 is an LMC555CN Timer IC connected as an Astable Multivibrator. Its output is a 0 – 9 VDC square wave at either 3.8 KHz (if Q2 is switched OFF) or 3.6 KHz (if Q2 is switched ON). U4 is another LMC555CN used as an inverter to drive the piezo buzzer SPK1 in a bridge fashion for greater output. R27/C8 is a glitch filter to prevent false triggering of U4. R25/R26 isolates the capacity of the piezo buzzer from the outputs of U1 and U4 to reduce unnecessary current spiking. The resistors are chosen for a 20 KHz upper limit for drive to SPK1. R14/C3 determine the high frequency of operation (3.8 KHz), R14/C3/C6 determine the low frequency (3.6 KHz), C6 being connected when Q2 is turned on.

U2 is a Holtek HT12E 2^12 encoder. Dip switches SW1 and SW2 program the bit pattern of U2. The data from U2 is used to switch Q2 ON and OFF.

For operation with an existing smoke detector, a peak detector consisting of Q4 and C5 captures a high level from a point in the smoke detector, which pulses during alarm conditions. Q3 is switched ON through R17 by the output of the peak detector, and in turn switches Q1 ON through R15. Q1 applies 9 VDC power to U1, U2 and U4. C2/C4/C7 are power supply bypass capacitors.

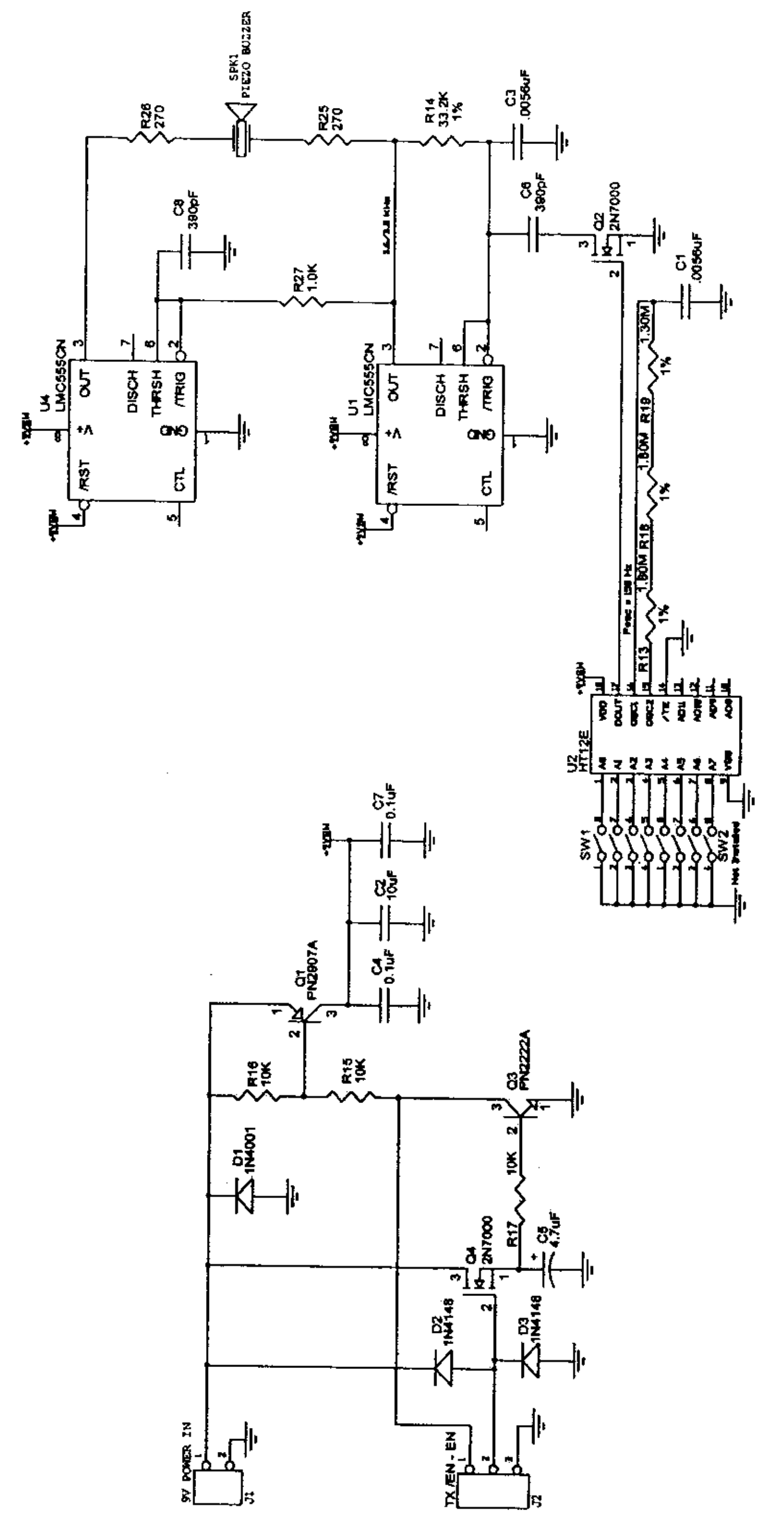

FIGURE 6. SONIC_TX_FM

B. FM Sonic Receiver

The Sonic FM Receiver design is shown in Figure 7. MIC1 is an electret microphone to receive the transmitted alarm signal, which is being switched between the two frequencies 3.6 kHz and 3.8 kHz. The signal from MIC1 goes through C23 to the bandpass filters at amplifier U2A and U2B and their surrounding resistors and capacitors. These filters have very little gain (3db) to avoid overloading from strong signals. The band passed signal from band pass filter U2A and U2B (selected for frequencies around 3.7 kHz) goes through C17 to the limiter consisting of D4/D5, then through C22 to the first limiting amplifier of U1, an SA604A an FM intermediate frequency (IF) system chip.

U1 has two stages of amplification, which serve to limit, or clip, the signal if it is strong enough. Limiting eliminates AM noise in the received signal but preserves the FM signal component. The total amplification is great enough that, even for the smallest input signals, the last stage of amplification is limiting. After amplification and limiting (if the signal is sufficiently strong) in the first amplifier of U1, the signal goes through the bandpass filter consisting of R26/C9/C10 and the 1.6 K internal impedance at U1 pin 12. This filter serves to reduce signal noise before the final limiting amplifier of U1. At the output of the final amplifier of U1 is the quadrature detector tuned circuit C7/C6/L1, with C8 for DC blocking. This circuit is adjusted using inductor L1 so that it has zero relative phase shift at 3.7 KHz. Inside U1 is a mixer circuit that compares the phase of the received signal to the phase seen at the tuned circuit. The tuned circuit response at the received frequencies 3.6 KHz and 3.8 KHz is negative and positive from zero phase. The signals from the internal mixer are seen at U1 pins 6 and 7, with pin 7 being an inverted version of pin. These two signals are raw, differential demodulated data. R18/R19/C13/R21 low-pass filter the differential demodulated data from U1, and U3 serves to slice the signal and produce a logic-level (0 – 4 V) output which transitions at the point where the two outputs from U1 are equal. The sliced data goes to the decoder U6.

U6 is a Holtek 2^12 decoder. The sliced data from U3 is applied to U6, which is enabled if the data pattern received matches that chosen by the dip switches SW1 and SW2. If U6 is enabled, Q3 is switched ON through R22. Q4 is then switched ON to short the pins of J3. J3 is connected across the test switch of the smoke detector, so the alarm is enabled.

Grounding J2 pin 1 switches Q1 ON through R15. Q1 applies 9 VDC power to the 5 VDC regulators ICs U4 and U5.

R31/D6/D7/D8/C25 are a bias supply for U2A and U2B stages.

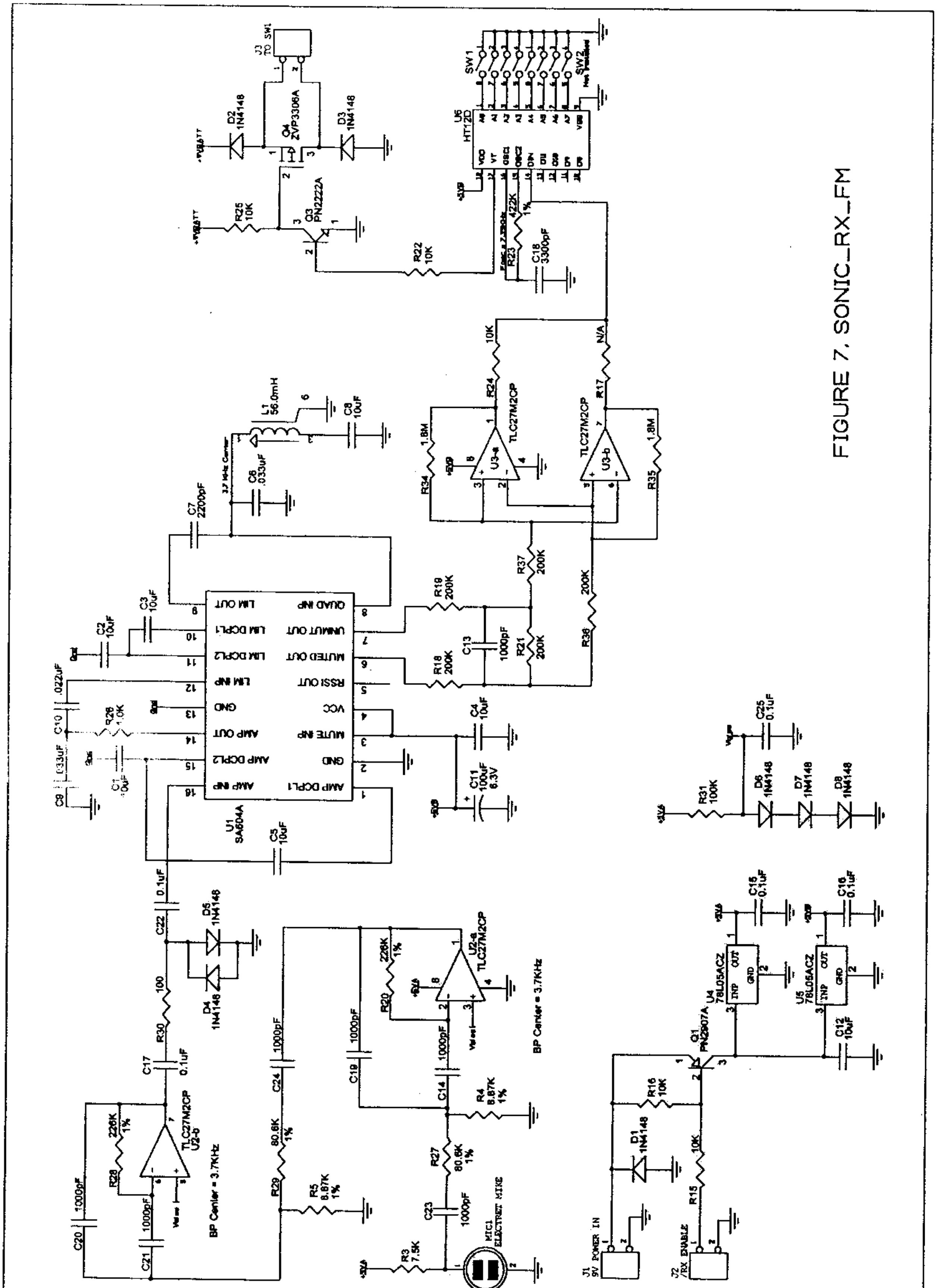

FIGURE 7. SONIC_RX_FM

4.2 Sonic Experimental Results

The Sonic version of the wireless smoke detector has been built and tested in two different forms, an Amplitude Modulated (AM) system and a Frequency Modulated (FM) system. The original system was AM but was redesigned as an FM system to address problems encountered during testing.

The sonic system, either AM or FM, was planned to use the existing smoke alarm piezoelectric buzzer as the "broadcast" element for transmission of a uniquely coded data stream. The receiver employs a microphone to pick up the alarm horn sound from other smoke alarms in the system, which is electronically processed and compared to a switch-selectable code sequence. If the received data has the appropriate code sequence, the receiving smoke alarm horn is enabled.

Testing of the AM system indicated that the transmitter piezoelectric buzzer was not properly broadcasting data. It was theorized that the (Q = energy per cycle/energy lost) of the buzzer was too high for the data rate employed. Slowing the data rate was one solution if the buzzer Q was at issue; unfortunately, the data rate was already the lowest deemed practical considering the length of the data encoding word being used. It was decided to build and test an FM system to see if buzzer Q would be less critical.

Testing of the FM system also indicated that the buzzer was not properly transmitting data. The buzzer was replaced with a small (2" diameter) electrodynamic speaker to test the theory. The system would operate but was very dependent on speaker positioning and on the angle between the speaker axis and the microphone axis. Several different speakers and microphones were employed with varying success. Our conclusion was that reverberant sound may be a problem with this system and an engineering refinement is needed to produce another wireless success. Due to funding limitations, the effort on the sonic technology was terminated before the desired performance was completed on the prototypes.

5.0 WIRELESS CIRCUITRY POWER CONSUMPTION

Modifications to battery powered residential smoke alarms integrating wireless communications capabilities must not alter or reduce the life of the smoke alarm's original battery, so an additional battery is used to power the alarm's wireless communication circuitry. A requirement exists for the additional battery to have a life of ten years. Normally, communication systems (receivers and transmitters) are continuously powered so communications can be accomplished at any time. To meet the ten-year battery life requirement, extraordinary measures must be taken to conserve the battery. Since the transmitter is only used when an alarm condition is met, it can be completely turned off until then, saving considerable battery power. Selectively powering the receiver on, at reasonable intervals, would conserve the battery even more. Several options exist to extend the life of the additional battery, and those are discussed below

5.1 RF Communications Power Consumption Options

Power Considerations for Implemented RF Circuitry:

```
1. RF Transmitter:   6.7 mA (MICRF102)
                     2.0 mA (78L05)
                     0.4 mA (HT12E)
                  +  1.0 mA (Miscellaneous)
                     ----------
                     10.1 mA.

2. RF Receiver:      3.0 mA (MICRF107)
                     2.0 mA (78L05)
                     0.2 mA (HT12D)
                  +  1.0 mA (Miscellaneous)
                     ----------
                     6.2 mA.
```

It is possible to reduce each by approximately 3 mA:

```
1. RF Transmitter:   6.7 mA (MICRF102)
                  +  0.4 mA (HT12E)
                     ----------
                     7.1 mA.

2. RF Receiver:      3.0 mA (MICRF007)
                  +  0.2 mA (HT12D)
                     ----------
                     3.2 mA.
```

The transmitter unit will only be activated during alarm conditions, so its active current draw is not of prime importance. The transmitter stand-by current can easily be made negligible, less than 10 nA. The receiver unit may be keyed ON in a low duty cycle fashion to minimize power. The receiver would remain ON and sound the alarm if the appropriate data word was being received. A 1% duty factor-for example, 1 second ON and 99 seconds OFF-would reduce the power consumed by the receiver to 0.032mA (32uA) average. Using a 1.2 Ah Lithium battery, this would result in a battery life of 4.28 years, neglecting self-discharge. Ten-year life might be achievable in this example by decreasing the duty factor to 0.4%, with an ON time of 1 second and an OFF time of 240 seconds. Although this approach will not lengthen the time for a smoke alarm to activate due to an alarm condition, it may lengthen the time for the alarm condition to be passed on to other smoke alarms in the network due to the receiver being disabled for an interval of time to save power. The receiver minimum ON time of 1 second is determined by the requirement that (at least) one entire data word be received in that time. Using higher data rates would minimize the time required to receive a data word but would adversely affect the range because of the greater bandwidth needed.

More sophisticated receiver control circuitry could potentially reduce the 1-second ON time to 0.1 second, and the 240 seconds OFF time to 24 seconds or less. This scheme would involve sensing only the presence of a carrier within the frequency range of the receiver. This can be done relatively quickly compared to sensing and verifying an entire data word transmission, so the initial ON time may be reduced to 100 ms, perhaps 50ms. If a carrier was sensed, the receiver would stay on long enough to verify that the appropriate data was being received. During carrier sense it would not be necessary that the HT12D decoder IC be operational, so it could be powered ON only if a carrier was present. This would reduce the receiver current consumption from 3.2 mA to 3 mA. For ten-year battery life with a 0.1 second ON time, the corresponding OFF time would then be 22 seconds. A further reduction in receiver ON time to 50 ms or less might be possible by switching the Automatic Gain Control (AGC) time constant capacitor (C5) and slicing level time constant (C6) values. During carrier sense, these values could be minimized to reduce receiver response time. If a carrier was sensed, the values could be switched to values appropriate for good data reception.

Also worth considering for power reduction is changing the operating frequency from 433 MHz, where the prototypes were tested, to closer to 300 MHz. At 433 MHz, the MICRF007 draws 3 mA; but at 300 MHz, the draw is only 1.7 mA. The tradeoff here is antenna length, especially at the receiver end. If the receiver antenna can be inserted into a hole in the ceiling to which the detector is attached, length would then be of less concern; and the lower frequency offers much better battery life. For example, with an ON time of 0.1 second, the corresponding OFF time for ten-year battery life would be 13 seconds.

5.2 Sonic Communication Power Consumption Options

Power considerations for implemented sonic circuitry:

1. Sonic Transmitter AM:

	0.3 mA (LMC555CN x 2)
	0.4 mA (SPK1 Drive)
+	8.0 mA (Bleeder R18) /2 (50% Duty Cycle)

	4.7 mA

2. Sonic Receiver AM:

	0.4 mA (TLC27M2CP x 2)
	0.5 mA (LMC567CN)
	0.2 mA (HT12D)
	6.0 mA (78L05 x 3)
+	1.0 mA (Miscellaneous)

	8.1 mA

3. Sonic Transmitter FM:

	0.3 mA (LMC555CN x 2)
	0.4 mA (HT12E)
+	2.0 mA (SPK1 Drive)

	2.7 mA

4. Sonic Receiver FM:

		3.3 mA (SA604A)
		0.4 mA (TLC27M2CP x 2)
	+	0.2 mA (HT12D)

		3.9 mA

Since the transmitter portion of these designs will only be activated during alarm conditions, its active current draw is not of prime importance. The transmitter standby current can easily be made negligible, less than 10 nA. Similar to the situation with the RF receiver, the sonic receiver unit may be keyed ON in a low duty-cycle fashion to minimize power. Many of the same considerations as with the RF receiver apply to optimizing and reducing the necessary sonic receiver ON time; for example, a carrier-sensing scheme would improve detection time and allow shorter ON and OFF times.

Other circuit topologies, for example using switched-capacitor filters instead of op-amps, could decrease the current draw and be more appropriate for integration of the circuitry into an Application Specific Integrated Circuit (ASIC). Conceivably the entire sonic receiver could be digital, with the microphone connected through a switched capacitor anti-aliasing filter to a high dynamic range analog to digital (A/D) converter, followed by digital processing. Existing digital signal processing technology used in satellite and telephone line modems could then be applied to address problems with reverberant sound and competing sound sources. The circuitry for such an all-digital sonic receiver could easily be integrated into a single chip.

6.0 DEMONSTRATION OF THE RF SMOKE ALARM PROTOTYPE

Three commercial battery powered smoke detectors were modified to operate with an RF receiver and transmitter allowing any one of the three detectors to transmit an alarm condition to the other detectors if an alarm condition was detected. The three units were thoroughly tested on the workbench prior to testing their capabilities in a house on the grounds of the Naval Research Laboratory. This house designated, "Quarters A," is a 2-story structure with a basement and was originally built in 1874. The construction is wood frame with plaster walls on metal lathing in place of wallboard found in current construction. The exterior is painted brick. The house's gross floor space is 3978 square feet. The house currently is used as a meeting and conference center and is divided into individual rooms that were previously used as: living, dining, sitting room, kitchen and bedrooms. It has a center hall way and the stairs to the upper floor are situated in the rear of the house in the center hallway. There is also a center hallway on the upper level with what were formerly bedrooms on either side.

An "X" in Figures 8 and 9 indicates placement of the modified residential smoke alarms. One unit was located in the kitchen, one in what was the living room (now a conference room) and one upstairs in the sitting room off the center hallway. The demonstration phase consisted of pressing the "alarm test button" on one of the units to activate the alarm horn and the RF circuitry and then making sure the other units responded to the alarm condition by also sounding their alarm horns and activating their RF transmitters. Each time one of the units initiated an alarm condition, the other detectors responded by sounding their alarm horn and activating their RF transmitters. Each of the three modified smoke alarms was forced into an alarm condition one at a time by pressing their "test buttons," and the remaining two alarms were monitored for a response. In each case, all three alarms responded in each test within seconds.

Initially, the three modified smoke detectors were tested in a 5000 + square ft., two story house with a finished basement. The construction was wood framing with wallboard on the inside and vinyl siding and brick on the outside. One detector was placed on each floor in various locations to test the RF transceiver's ability to transmit and receive alarm conditions through walls and floors. Each of these units was able to initiate an alarm condition in the other units via the RF connection, even when the detectors were separated by numerous walls and obstacles and on different floors. These initial tests were fully successful and, in each test, generated an alarm response from each of the other modified units by either direct communication or by relay from one unit to another.

7.0 COST OF PARTS TO IMPLEMENT WIRELESS COMMUNICATION PROTOTYPES

A requirement of this research effort is to determine the cost of implementing each wireless communications approach. It was determined that a suitable quantity to base the component cost on would be for the manufacture of at least 1000 units. Therefore if a board contained one of a particular part, 1000 would be needed. The cost of the part, at that quantity, would be used in determining price for that part. If the board contained five of a particular part, then 5000 would be needed; and that quantity would be used to determine the price for that part. A complete parts list was assembled for each receiver/transmitter board for the RF and Sonic Designs. Using the formula above the prices were ascertained and recorded in a table for each part on each board. A total price for the parts needed to build 1000 of each board is shown in Table 1 thru Table 6 in Appendix A. A national company manufacturing smoke alarms for sale may build hundreds of thousands of alarms, resulting in significant additional savings on these parts.

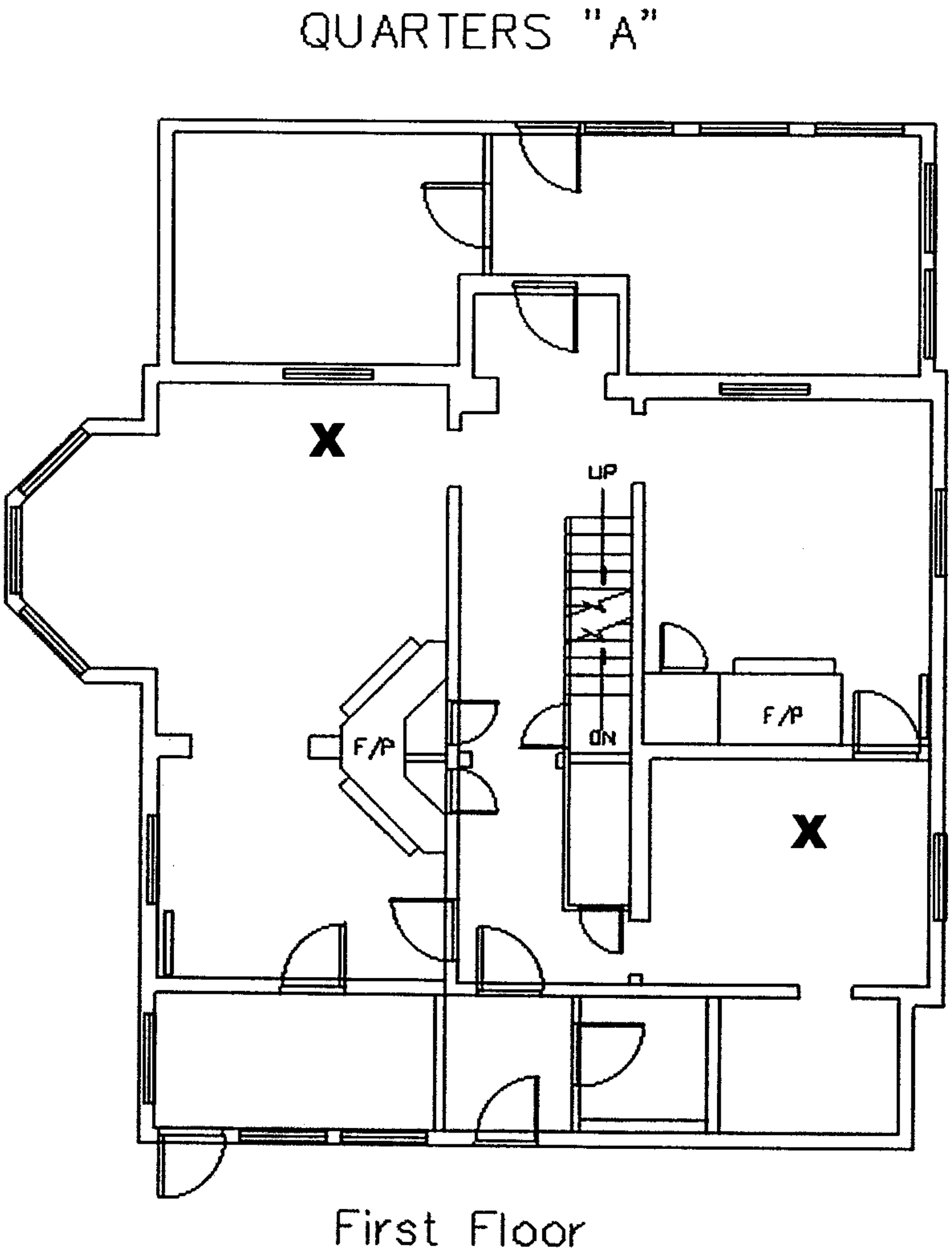

FIGURE 8. QUARTERS 'A' FIRST FLOOR SMOKE ALARM LOCATIONS

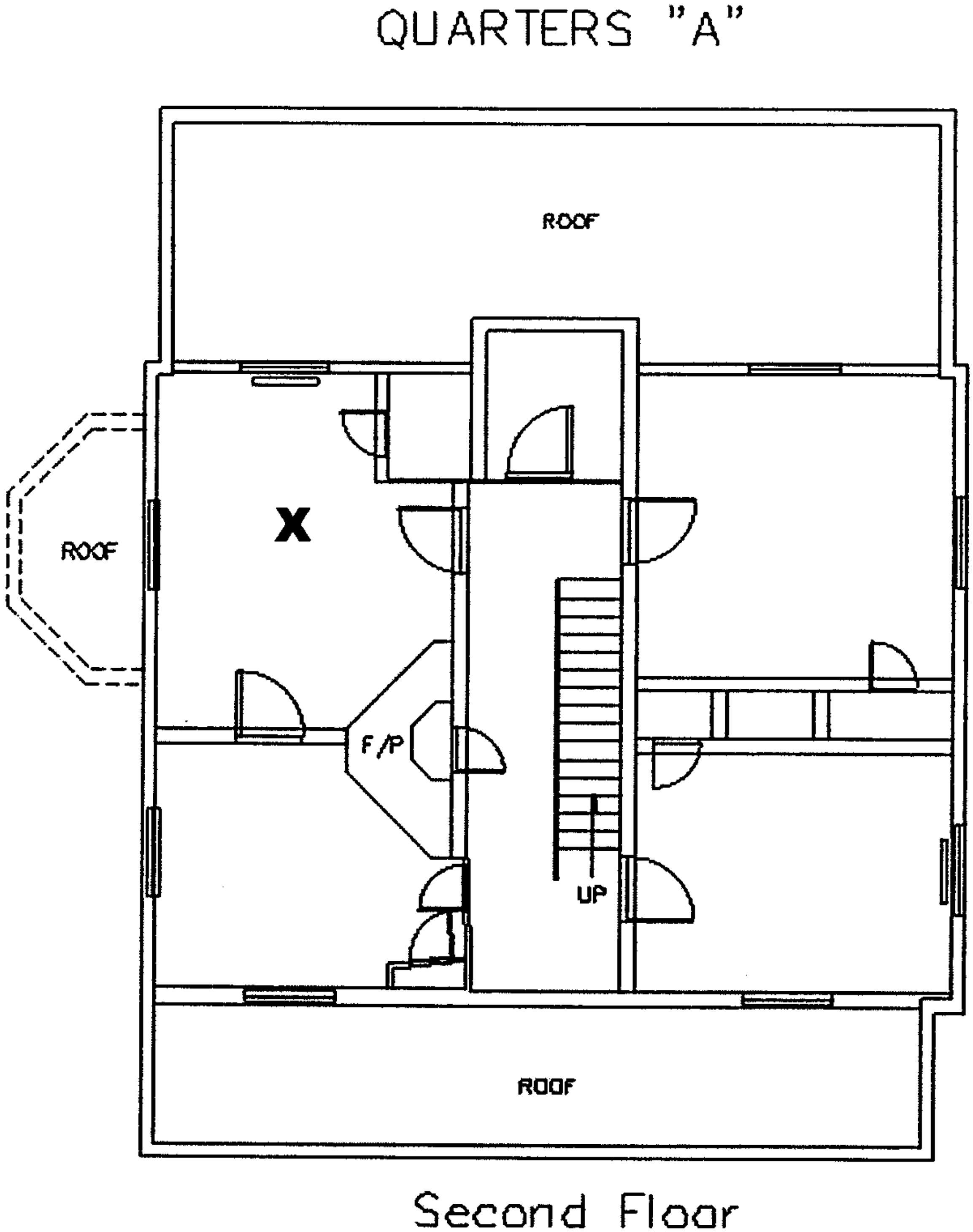

FIGURE 9. QUARTERS 'A' SECOND FLOOR SMOKE ALARM LOCATIONS

8.0 CONCLUSIONS AND RECOMMENDATIONS

General: Power consumption remains an issue and requires trade-offs. The military is working on microelectronics that consumes less power. In addition, battery technologies continue to make advances in weight-to-power density.

RF Communications:

An RF Receiver/Transmitter prototype design capable of being integrated into an existing battery powered, residential smoke alarm has been developed; and it tested favorably in several residences. This design allows any smoke alarm that detects fire conditions to communicate that condition to all smoke alarms in the system when only one of them detects fire conditions. The costs of implementing this design (prices based on procurement of 1000 units), see Table 1 and 2 in the Appendix, using separate circuit boards are estimated to be $4.52 for the transmitter board and $5.91 for the receiver board. If the manufacturers of battery-powered smoke alarms integrated the RF communications design into their circuit boards using an ASIC chip, the cost of implementation could be much lower.

Operational tests have indicated the ability of this design to effectively communicate alarm conditions between smoke detectors positioned within a residence. The unique coding of the RF transmitted alarm condition helps prevent false alarming. Any interference encountered by other household devices could be minimized by narrowband filtering, changes in frequency of operation or extending the unique code to include more code depth. An RF implementation is an excellent choice for wireless communications to communicate alarm conditions between smoke detectors in a system.

Sonic Communications:

Sonic communications of smoke detector alarm conditions is a concept in which the smoke detector alarm horn would be used as the transmitter in a wireless communication system. By detecting the presence of an audible alarm horn from an alarming smoke alarm, other smoke alarms could be forced into an alarm condition to advance the alarm condition throughout the building. Several sonic design approaches have been implemented and tested to communicate alarm conditions between smoke detectors in a system. Several design modifications were implemented to address problems encountered during testing of these designs. It has been determined that changes and improvements in several areas are needed to produce another wireless approach for smoke detector communications. The following steps are appropriate to refine the sonic communication approach:

1) Optimize the piezoelectric buzzer by obtaining and implementing a variety of buzzers, including high-fidelity piezoelectric speakers at the transmitter.

2) Obtain and implement a variety of microphones, including omni-directional and various types of directional, at the receiver.

3) Redesign the receiver digital processing section to more effectively deal with delayed data caused by reverberant sound.

4) Study the operation in an anechoic environment, either in an appropriate sound chamber or out-of-doors, to further understand reverberant sound effects in this application.

9.0 ACKNOWLEDGEMENTS

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APPENDIX A

COST TO IMPLEMENT WIRELESS COMMUNICATION DESIGNS

COST OF PARTS

Item Number	Part Name	Part Number	Value	Schematic Designation	Quanity	Cost Each	Cost Total
1	Voltage Regulator	78L05ACZ		U3	1	$0.13	$0.13
2	Capacitor	ECS-F1AE475K	4.7 uF	C5	1	$0.23	$0.23
3	Capacitor	ECJ-2VC1H101J	100 pF	C1	1	$0.02	$0.02
4	Capacitor	ECJ-4YB1C106K	0.1 uF	C2,C4	2	$0.06	$0.12
5	Capacitor	ECJ-4YB1C106K	10 uF	C3,C7	2	$0.31	$0.62
6	Capacitor	1206CG279C9B200	2.7 pF	C6	1	$0.03	$0.03
7	Capacitor	1206CG399C9B200	3.9 pF	C8	1	$0.03	$0.03
8	Diode	1N4001		D1	1	$0.02	$0.02
9	2^12 Dncoder	HT12E-18		U2	1	$0.40	$0.40
10	UHF RX	MICRF002BM		U1	1	$1.25	$1.25
11	NPN Transistor	PN2222A		Q2	1	$0.07	$0.07
12	PNP Transistor	PN2907A		Q1	1	$0.06	$0.06
13	N CH MOSFET	2N7000		Q3	1	$0.07	$0.07
14	Resistor	ERJ-3GEYJ104V	100K	R11	1	$0.01	$0.01
15	Resistor	ERJ-3GEYJ682V	6.8K	R12	1	$0.01	$0.01
16	Resistor	ERJ-3EKF1104V	1.1M	R13	1	$0.01	$0.01
17	Resistor	ERJ-3GEYJ103V	10K	R15-R17	3	$0.01	$0.03
18	DIP Switch	209-4MS		SW1	1	$0.41	$0.41
19	Quartz Crystal	AB-6.7459MHZ-20-D	13.560 MHz	Y1	1	$0.32	$0.32
20	Circuit Board	RF Transmitter			1	$0.68	$0.68
					Total	$ 4.13	$ 4.52

Table 1, RF Transmitter Parts List

COST OF PARTS

Item Number	Part Name	Part Number	Value	Schematic Designation	Quanity	Cost Each	Cost Total
1	Voltage Regulator	78L05ACZ		U3	1	$0.13	$0.13
2	Capacitor	ECS-F1AE475K	4.7 uF	C5	1	$0.23	$0.23
3	Capacitor	ECJ-2VC1H101J	100 pF	C1	1	$0.19	$0.19
4	Capacitor	ECS-F1AE225K	2.2 uF	C6,C7	2	$0.18	$0.36
5	Capacitor	ECJ-4YB1C106K	10 uF	C3	1	$0.34	$0.34
6	Capacitor	ECJ-3VB1E104K	.1 uF	C2,C4	2	$0.08	$0.16
7	Diode	1N4001		D1	1	$0.03	$0.03
8	2^12 Dncoder	HT12D-18		U2	1	$0.54	$0.54
9	UHF RX	MICRF007BM		U1	1	$1.88	$1.88
10	NPN Transistor	PN2222A		Q2,Q3	2	$0.07	$0.14
11	PNP Transistor	PN2907A		Q1	1	$0.06	$0.06
12	P CH MOSFET	ZVP3306A		Q4	1	$0.24	$0.24
13	Resistor	5063JD68K10F12AF5	68.1K	R13	1	$0.08	$0.08
14	Resistor	CFR-12JB-10K	10K	R14-R19	6	$0.02	$0.12
15	DIP Switch	209-4MS		SW1	1	$0.41	$0.41
16	Quartz Crystal	AB-6.7459MHZ-20-D	6.7459 MHz	Y1	1	$0.32	$0.32
17	Circuit Board	RF Receiver			1	$0.68	$0.68
					Total	$ 5.48	$ 5.91

Table 2, RF Receiver Parts List

COST OF PARTS

Item Number	Part Description	Part Number	Value	Schematic Designation	Quanity	Cost Each	Cost Total
1	RC Timer	LMC555CN		U1,U4	2	$0.18	$0.36
2	Capacitor	ECS-F1AE475K	4.7 uF	C5	1	$0.22	$0.22
3	Capacitor	PCF1110CT-ND	.0056 uF	C1,C3	2	$0.44	$0.88
4	Capacitor	ECJ-4YB1C106K	10 uF	C2	1	$0.34	$0.34
5	Capacitor	ECJ-3VB1E104K	.1 uF	C4.C7	2	$0.07	$0.14
6	Capacitor	ECJ-1VC1H391J	390 pF	C6,C8	2	$0.04	$0.08
7	Diode	1N4001		D1	1	$0.03	$0.03
8	Diode	1N4148		D2,D3	2	$0.02	$0.04
9	2^12 Encoder	HT12E-18		U2	1	$0.40	$0.40
10	N CH MOSFET	2N7000		Q2,Q4	2	$0.07	$0.14
11	NPN Transistor	PN2222A		Q3	1	$0.07	$0.07
12	PNP Transistor	PN2907A		Q1	1	$0.05	$0.05
13	Piezo Buzzer	EFB-RD22C415		SPK1	1	$0.99	$0.99
14	Resistor	ERJ-6ENF1804V	1.80 M	R13,R18	2	$0.02	$0.04
15	Resistor	ERJ-3EKF3322V	33.2K	R14	1	$0.02	$0.02
16	Resistor	ERJ-3GEYJ102V	1.0K	R27	1	$0.02	$0.02
17	Resistor	ERJ-3GEYJ103V	10K	R15,R17	2	$0.02	$0.04
18	Resistor	ERJ-6ENF1304V	1.30M	R19	1	$0.02	$0.02
19	Resistor	ERJ-3GEYJ271V	270	R25,R26	2	$0.02	$0.04
20	DIP Switch	209-4MS		SW1	1	$0.40	$0.40
21	Circuit Board	Sonic AM Transmitter			1	$0.68	$0.68
					Total	$ 4.12	$ 5.00

Table 3, Sonic AM Transmitter Parts List

COST OF PARTS

Item Number	Part Description	Part Number	Value	Schematic Designation	Quanity	Cost Each	Cost Total
1	Voltage Regulator	78L05ACZ		U4-6	3	$0.13	$0.39
2	FM IF System	SA604A		U1	1	$2.75	$2.75
3	Capacitor	ECS-F0JE107	100 uF	C7,C13	2	$1.22	$2.44
4	Capacitor	ECS-F1AE225K	2.2 uF	C14	1	$0.18	$0.18
5	Capacitor	ECJ-3VB1E224K	.22 uF	C10	1	$0.09	$0.09
6	Capacitor	ECJ-3VB1E104K	.1 uF	C1, C8-9,C15-17,C19	7	$0.06	$0.42
7	Capacitor	ECJ-2VC1H102J	1000 pF	C4-6,C11-12	5	$0.04	$0.20
8	Capacitor	ECJ-3VC1H332J	3300 pF	C18	1	$0.58	$0.58
9	Inductor	CLNS-T1039Z	56.0mh	L1	1	$1.02	$1.02
10	Diode	1N4001		D1	1	$0.02	$0.02
11	2^12 Decoder	HT12D-18		U7	1	$0.54	$0.54
12	Tone Decoder	LMC567CN		U1	1	$0.78	$0.78
13	P CH MOSFET	ZVP3306A		Q4	1	$0.23	$0.23
14	Dual Op-Amp	TLC27M2CP		U2,U3	2	$0.34	$0.68
15	NPN Transistor	PN2222A		Q2,Q3	2	$0.07	$0.14
16	PNP Transistor	PN2907A		Q1	1	$0.05	$0.05
17	N CH MOSFET	2N7000		Q5	1	$0.07	$0.07
18	Resistor	5063JD1M100F12AF5	1.10 M	R7,R9	2	$0.07	$0.14
19	Resistor	5063JD422K0F12AF5	422K	R22	1	$0.07	$0.07
20	Resistor	5063JD301K0F12AF5	301K	R13	1	$0.08	$0.08
21	Resistor	5063JD100K0F12AF5	100K	R11,R18	2	$0.08	$0.16
22	Resistor	5063JD86K60F12AF5	86.6K	R15	1	$0.07	$0.07
23	Resistor	5063JD49K90F12AF5	49.9K	R8,R17	2	$0.07	$0.14
24	Resistor	5063JD24K90F12AF5	24.9K	R10,R12	2	$0.07	$0.14
25	Resistor	CFR-12JB-10K	10K	R16,R19,R21,R23-25,R27	7	$0.02	$0.14
26	Resistor	5063JD3K010F12AF5	3.01K	R14	1	$0.07	$0.07
27	Resistor	5063JD7K500F12AF5	7.5K	R20,R26	2	$0.07	$0.14
28	DIP Switch	209-4MS		SW1	1	$0.40	$0.40
29	Electret Mike	WM-54BT		MIC1	1	$0.39	$0.39
30	Circuit Board	Sonic AM Receiver			1	$0.68	$0.68
					Total	$ 10.31	$ 13.20

Table 4, Sonic AM Receiver Parts List

COST OF PARTS

Item Number	Part Description	Part Number	Value	Schematic Designation	Quanity	Cost Each	Cost Total
1	RC Timer	LMC555CN		U1,U4	2	$ 0.18	$ 0.36
2	Capacitor	ECS-F1AE475K	4.7 uF	C5	1	$0.22	$0.22
3	Capacitor	ECJ-2VC1H101J	.0056 uF	C1,C3	2	$0.44	$0.88
4	Capacitor	ECS-F1AE225K	2.2 uF	C9	1	$0.18	$0.18
5	Capacitor	ECJ-4YB1C106K	10 uF	C2	1	$0.34	$0.34
6	Capacitor	ECJ-3VB1E104K	.1 uF	C4.C7	2	$0.07	$0.14
7	Capacitor	ECJ-1VC1H391J	390 pF	C6,C8	2	$0.04	$0.08
8	Capacitor	ECJ-2VC1H102J	1000 pF	C19	1	$0.04	$0.04
9	Diode	1N4001		D1	1	$0.06	$0.06
10	Diode	1N4148		D2,D3	2	$0.02	$0.04
11	2^12 Encoder	HT12E-18		U2	1	$0.40	$0.40
12	N CH MOSFET	2N7000		Q2,Q4	2	$0.07	$0.14
13	NPN Transistor	PN2222A		Q3	1	$0.07	$0.07
14	PNP Transistor	PN2907A		Q1	1	$0.06	$0.06
15	Piezo Buzzer	EFB-RD22C415		SPK1	1	$0.99	$0.99
16	Resistor	ERJ-6ENF1804V	1.80 M	R13,R18	2	$0.02	$0.04
17	Resistor	ERJ-3EKF3092V	30.9K	R14	1	$0.02	$0.02
18	Resistor	ERJ-3GEYJ102V	1.0K	R15,R27	2	$0.02	$0.04
19	Resistor	ERJ-3GEYJ103V	10K	R16,R17	2	$0.02	$0.04
20	Resistor	ERJ-6ENF1304V	1.30M	R19	1	$0.02	$0.02
21	Resistor	ERJ-3GEYJ271V	270	R25,R26	2	$0.02	$0.04
22	DIP Switch	209-4MS		SW1	1	$0.40	$0.40
23	Circuit Board	Sonic FM Transmitter			1	$0.68	$0.68
					TOTAL	$ 4.38	$ 5.28

Table 5, Sonic FM Transmitter Parts List

COST OF PARTS

Item Number	Part Description	Part Number	Value	Schematic Designation	Quanity	Cost Each	Cost Total
1	Voltage Regulator	78L05ACZ		U4,U5	2	$0.13	$0.26
2	FM IF System	SA604A		U1	1	$2.75	$2.75
3	Capacitor	ECS-F0JE107	100 uF	C11	1	$0.22	$0.22
4	Capacitor	ECH-U1C333JB5	.033 uF	C6,C9	2	$0.22	$0.44
5	Capacitor	ECH-U1C223JX5	.022 uF	C10	1	$0.22	$0.22
6	Capacitor	ECJ-4YB1C106K	10 uF	C1-C5,C8,C12	7	$0.20	$1.40
7	Capacitor	ECJ-3VB1E104K	.1 uF	C15-17,C22,C25	5	$0.07	$0.35
8	Capacitor	ECJ-2VC1H222J	2200 pF	C7	1	$0.08	$0.08
9	Capacitor	ECJ-2VC1H102J	1000 pF	C13,C14,C19-21,C23,C24	7	$0.04	$0.28
10	Capacitor	ECJ-3VC1H332J	3300 pF	C18	1	$0.58	$0.58
11	Inductor	CLNS-T1039Z	56.0mh	L1	1	$1.02	$1.02
12	Diode	1N4148		D1-8	8	$0.08	$0.64
13	2^12 Decoder	HT12D-18		U6	1	$0.54	$0.54
14	P CH MOSFET	ZVP3306A		Q4	1	$0.21	$0.21
15	Dual Op-Amp	TLC27M2CP		U2,U3	2	$0.34	$0.68
16	NPN Transistor	PN2222A		Q3	1	$0.07	$0.07
17	PNP Transistor	PN2907A		Q1	1	$0.06	$0.06
18	Resistor	ERJ-3GEYJ185V	1.80 M	R34,R35	2	$0.01	$0.02
19	Resistor	ERJ-3EKF4223V	422K	R23	1	$0.02	$0.02
20	Resistor	ERJ-3GEYJ204V	200K	R18-19,R21,R36-37	5	$0.01	$0.05
21	Resistor	ERJ-3EKF2263V	226K	R20,R28	2	$0.01	$0.02
22	Resistor	ERJ-3GEYJ104V	100K	R31	1	$0.02	$0.02
23	Resistor	ERJ-3EKF8062V	80.6K	R27,R29	2	$0.02	$0.04
24	Resistor	ERJ-3GEYJ102V	1.0K	R26	1	$0.02	$0.02
25	Resistor	ERJ-3GEYJ103V	10K	R15-16,R22,R24-25	5	$0.02	$0.10
26	Resistor	ERJ-3EKF8871V	8.87K	R4,R5	2	$0.02	$0.04
27	Resistor	ERJ-GEYJ752V	7.5K	R3	1	$0.01	$0.01
28	Resistor	ERJ-3GEYJ101V	100	R30	1	$0.02	$0.02
29	DIP Switch	209-4MS		SW1	1	$0.40	$0.40
30	Electret Mike	WM-54BT		MIC1	1	$0.39	$0.39
31	Circuit Board	Sonic FM Receiver			1	$0.68	$0.68
					Cost Total	$ 8.48	$ 11.63

Table 6, Sonic FM Receiver Parts List