Application Report
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DTMF-Controlled Remote Switching Application Using the MSP430

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ABSTRACT

This reference design demonstrates how the MSP430 ultra-low power, mixed signal processor can be used to perform the real-time signal processing necessary to implement a dual tone multi-frequency (DTMF) decoding application. A DTMF decoding algorithm, which uses wave digital filters to process electrical signals sampled from a telephone line, forms the core of the remote touch-tone phone controlled switch application whose construction and function are discussed in this report. The ADC10 peripheral available on the MSP430F1232 is used to perform the sampling and conversion of telephone line voltages, while the Timer_A peripheral is used to generate square waves to output notification tones onto the telephone line.

1 Introduction

This MSP430 application connects to an ordinary analog telephone line in parallel to a user phone and allows the user to control eight electric switches by making a call to the phone to which the MSP430 device is attached and punching in an access code and simple instruction sequence to turn any of the eight lines on or off. In other words, one could remotely turn on the sprinklers in one's lawn or the air conditioning at home, or turn off the lights mistakenly left on in one's apartment if they are each connected to one of the telephone-controlled switching outputs on the MSP430 application.

The requirements for building an application like the one described previously include hardware to form the interface between the telephone line and the MSP430 microcontroller, signal processing capabilities, provided by the MSP430, for deciphering information encoded as electrical signals on the telephone line, and a control program for the MSP430.

2 Decoding DTMF

2.1 DTMF

Dual tone multi-frequency (DTMF) is a scheme for encoding 16 characters using the sums of sinusoidal signals of two distinct, harmonically unrelated frequencies. The following table shows how the 16 characters are each represented by one frequency from a low frequency group (ranging from 697 Hz to 941 Hz) and one from a high frequency group (ranging from 1209 Hz to 1633 Hz).

Table 1. The DTMF encoding scheme

Frequency	1209 Hz	1336 Hz	1477 Hz	1633 Hz
697 Hz	1	2	3	A
770 Hz	4	5	6	B
852 Hz	7	8	9	C
941 Hz	* (E)	0	# (F)	D

DTMF is widely used in telecommunication systems. To transmit a particular character on a telephone line, the two frequencies representing that character are generated as electrical signals, added and sent down the line. A specified period of silence (40 milliseconds or more) separates one transmitted DTMF character from another. A receiving device decodes the character being transmitted by identifying the two frequencies present in each sum it receives.

2.2 Identifying DTMF Signals

To identify the DTMF character received by the MSP430 application, the analog voltage signal on the telephone line is sampled and converted to a digital value using the 10-bit analog-to-digital converter (ADC10) peripheral on the MSP430F1232 chip. The sampling frequency used is 3640 Hz, which is more than two times the highest DTMF frequency. This satisfies the Nyquist criterion and therefore ensures that the integrity of the signal is preserved after sampling. The sampled signal is then passed through each of 8 wave digital filters to identify which two DTMF frequencies, if any, are present in the sampled signal.

2.3 Wave Digital Filters

The digital processing of voltage signals eliminates the need for additional circuitry external to the MSP430 for implementing analog filters. Wave digital filters are used, which are implemented in software and have many desirable features such as response stability and good dynamic range.

A DTMF decoding algorithm for the MSP430 **[1]** makes use of 8 wave digital filters, which are conveniently implemented with shift-and-add multiplications to eliminate the need for a hardware multiplier. Each of the filters is designed to have a resonant frequency corresponding to one of the DTMF frequencies. Thus, a signal whose frequency matches the resonant frequency of the filter it is passed through will be magnified by a known factor characteristic to the filter, while noise and signals of all other frequencies will be significantly attenuated. The output of a filter can then be analyzed to determine if a particular frequency was present in a signal or not.

3 Hardware

3.1 Function of Circuit Components

The circuit schematic in Figure 1 shows the hardware that interfaces the tip and ring telephone lines with the MSP430, the JTAG interface, and 8 LEDs for demonstrating the switching action of the application.

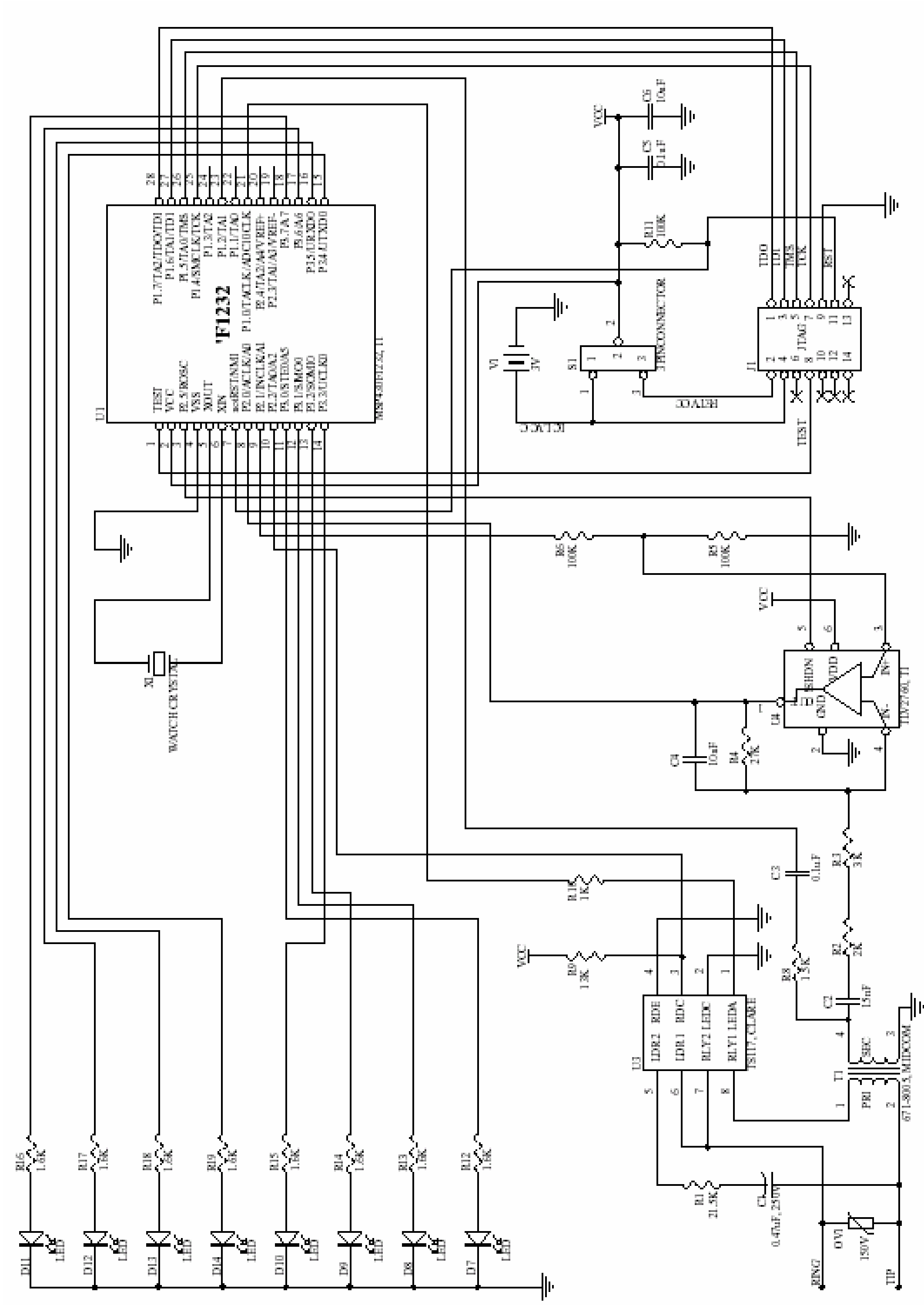
The interface between the phone line and the MSP430 consists of four functional parts:

- **Ring detection:** U3 combines the ring detect function and a solid-state relay for implementing the telephone hookswitch in one IC. The capacitor C1 dc-filters the 15-Hz ring signal from the telephone line, which is then passed through the current-limiting resistor R1 into the ring detect portion of U3. When there is no ring signal on the phone line, the ring detect output maintains a logic high. A logic low value on the output indicates a detected telephone ring. The ring detect output of U3 is connected to an MSP430 I/O pin (pin 10) to generate an interrupt to the MSP430 on each telephone ring.
- **Hookswitch**: A dedicated I/O pin (pin 21) on the MSP430 is connected to the relay control pin of U3. It is used to turn the solid-state relay portion of U3 on or off, to close or open the circuit on the primary side of the transformer T1.
- **DTMF input line:** This comprises the secondary side of the transformer T1, feeding into the operational amplifier (op amp) input and from the op amp output to pin 8 (ADC channel A0) of the MSP430. Since DTMF signals are ac signals, they are propagated from the telephone line on the primary side of T1 to the secondary side. The signal path through R8 and C3 to pin 23 of the MSP430 is blocked to DTMF signals by placing I/O pin 23 in a high impedance mode when receiving DTMF. DTMF signals thus pass through the dc-filtering capacitor C2, are amplified by U4 and sampled at pin 8 of the MSP430. The op amp U2 also biases the amplified DTMF signals at VCC/2 to enable the analog-to-digital converter to convert samples from the upper as well as the lower half-cycles of the ac signal.
- **Notification tone output line:** This is the path for square wave signals generated as user notification tones by the MSP430 Timer_A peripheral. The op amp U4 is shut down by driving the shutdown pin on the op amp low and the op amp outputs are placed in a high impedance mode, when a user notification tone is being output. The square wave goes through C3, R8 and the secondary side of T1, and is propagated to the primary side and to the telephone line, which transmits it to the user's earpiece.

The JTAG interface provides the appropriate signal connections for in-system programming of the MSP430 **[2]** via a PC parallel port. The jumper switch S1 provides the option of powering the board either from the on-board battery V1, or from a PC connected via the JTAG interface.

The eight LEDs, D7 to D14, are connected to MSP430 output pins through current limiting resistors R12 to R19. They can be turned on or off by the MSP430 to demonstrate the switching function of the application.

Figure 1. Circuit Schematic



3.2 Parts list

Table 2. Bill of Materials

Designator	Part Type	Part Ratings	Part Number
C1	Capacitor	0.47uF, 250V	
C2	Capacitor	15nF	
C3, C5	Capacitor	0.1uF	
C4	Capacitor	10nF	
C6	Capacitor	10uF	
D7 to D14	LED	3mA	HLMP-D150A
J1	14-pin header		2514-6002UB
OV1	Varistor	150V	
R12 to R19	Resistor	1.6K	
R1	Resistor	21.5K	
R9	Resistor	13K	
R10	Resistor	1K	
R8	Resistor	1.5K	
R2	Resistor	2K	
R3	Resistor	3K	
R4	Resistor	27K	
R5, R6, R11	Resistor	100K	
S1	3-pin header		
T1	Transformer		MIDCOM, 671-8005
U1	Mixed signal processor		TI, MSP430F1232
U4	Opamp		TI, TLV2760
U3	SSR, ring detect IC		Clare, TS117
V1	Battery	3V	
X1	Watch crystal	32768 Hz	

4 Software

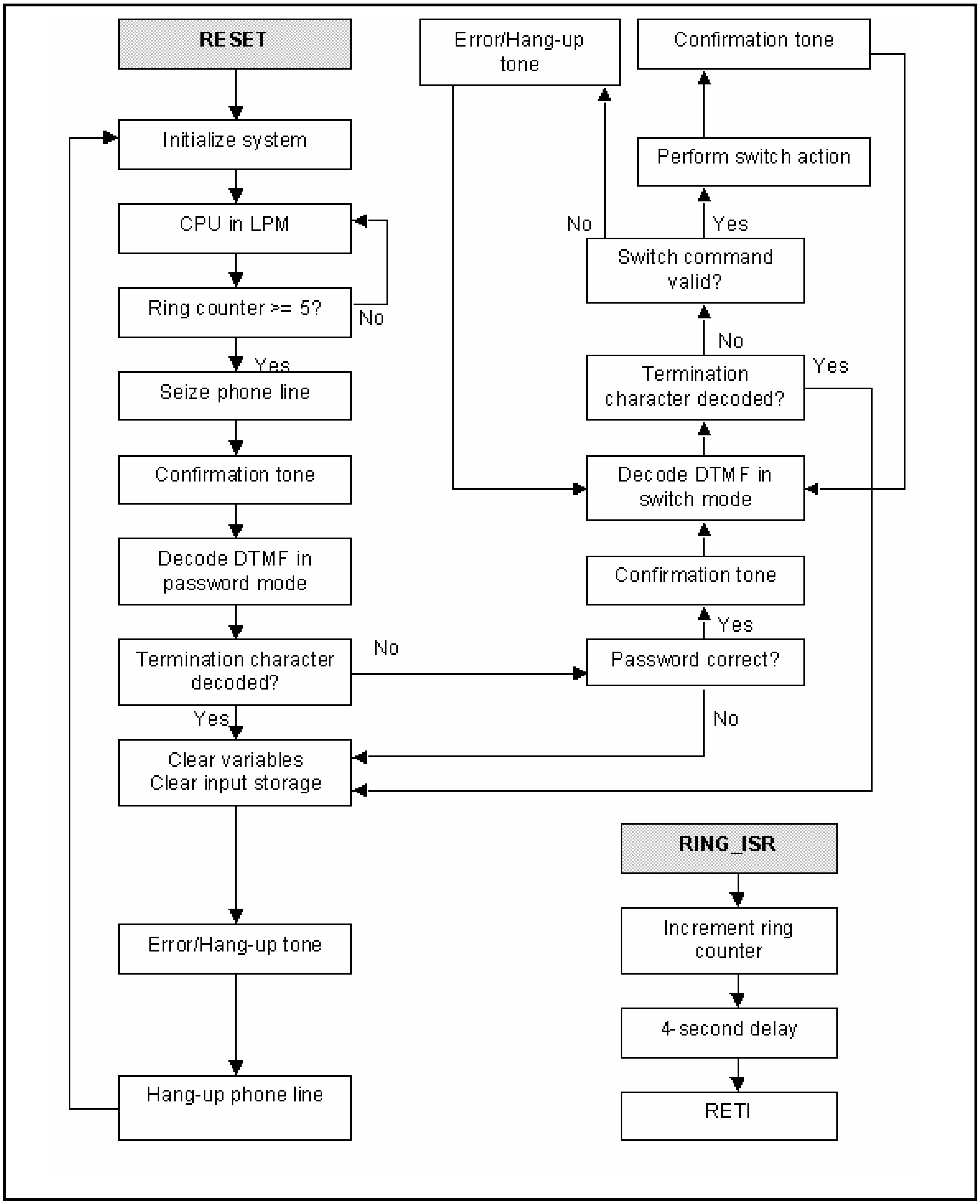
4.1 Main Program for Controlling the MSP430

The MSP430 CPU is run at a frequency between 4.4 MHz and 5.4 MHz by setting the on-chip digitally controlled oscillator (DCO) to run at the maximum settings (see the data sheet for the MSP430F1232 device **[5]**). This CPU frequency is adequate for the application, since the sampling frequency is obtained from a more precise 32768-Hz ACLK signal. Counter variables are cleared and the CPU is turned off to wait for ring interrupts. A ring counter is incremented in the ring interrupt service routine. Most standard ring cadences have a 6-second period (this application was tested with a typical ring cadence of 2 seconds on and 4 seconds off). The return from the ring interrupt service routine (inside of which ring interrupts are disabled) is delayed for 4 seconds using the watchdog timer available on the MSP430. This delay ensures that a single ring is not counted multiple times due to a fluctuating ring detect signal with multiple falling edges causing multiple ring interrupts to be generated.

Ring signals are counted until the specified number is obtained (5, in this implementation). The application then seizes the telephone line and confirms this to the user with a tone. The user has one chance to enter a correct password, and if there is a password match, the application runs in switch mode, where it accepts and executes valid DTMF signals representing switch actions requested.

On the demonstration board, 8 LEDs are turned on or off to show the switching action. In a real-world product the 8 outputs can be used to turn low current solid-state relays to turn isolated circuits on or off.

Figure 2. Flow Chart of Control Program



4.2 DTMF Decoding Algorithm [1]

Timer_A triggers the analog-to-digital converter on the MSP430 to sample the voltage level on channel A0 at intervals of 274.7μs. In the time between two samples, the current sample is used to calculate the 8 filter outputs to identify two maximum values from the high and low frequency groups in the DTMF table. Twenty filtering cycles are carried out to allow all the filters to reach a steady state and the various frequencies to go through their peak amplitudes. (20 cycles correspond to 20 x 0.2747 ms = 5.494 ms, which is longer than the largest DTMF signal period of 1.435 ms for the 697-Hz wave.) After consolidating these 20 samples, a check is performed to determine that the two maximum filter output values chosen both lie above the natural noise level. Another check is performed to make sure that the difference between the two values is not excessive.

Each time a valid DTMF frequency combination is thus identified, a signal length counter is incremented until the required signal length is reached. This means 8 iterations of this procedure are required to ensure that the 40 ms must-recognize DTMF specification is met. A flag is set when a DTMF tone of appropriate length is identified.

When no DTMF tone is recognized after a set of 20 filter runs, the signal length counter is decremented. The DTMF flag is cleared when the signal length reaches 0, and this indicates a valid pause between DTMF characters.

For an in-depth description of the DTMF decoding algorithm for the MSP430, refer to *Generation and Recognition of DTMF Signals with the Microcontroller MSP430* **[1]**.

Figure 3. Flow Chart of Algorithm for Decoding DTMF

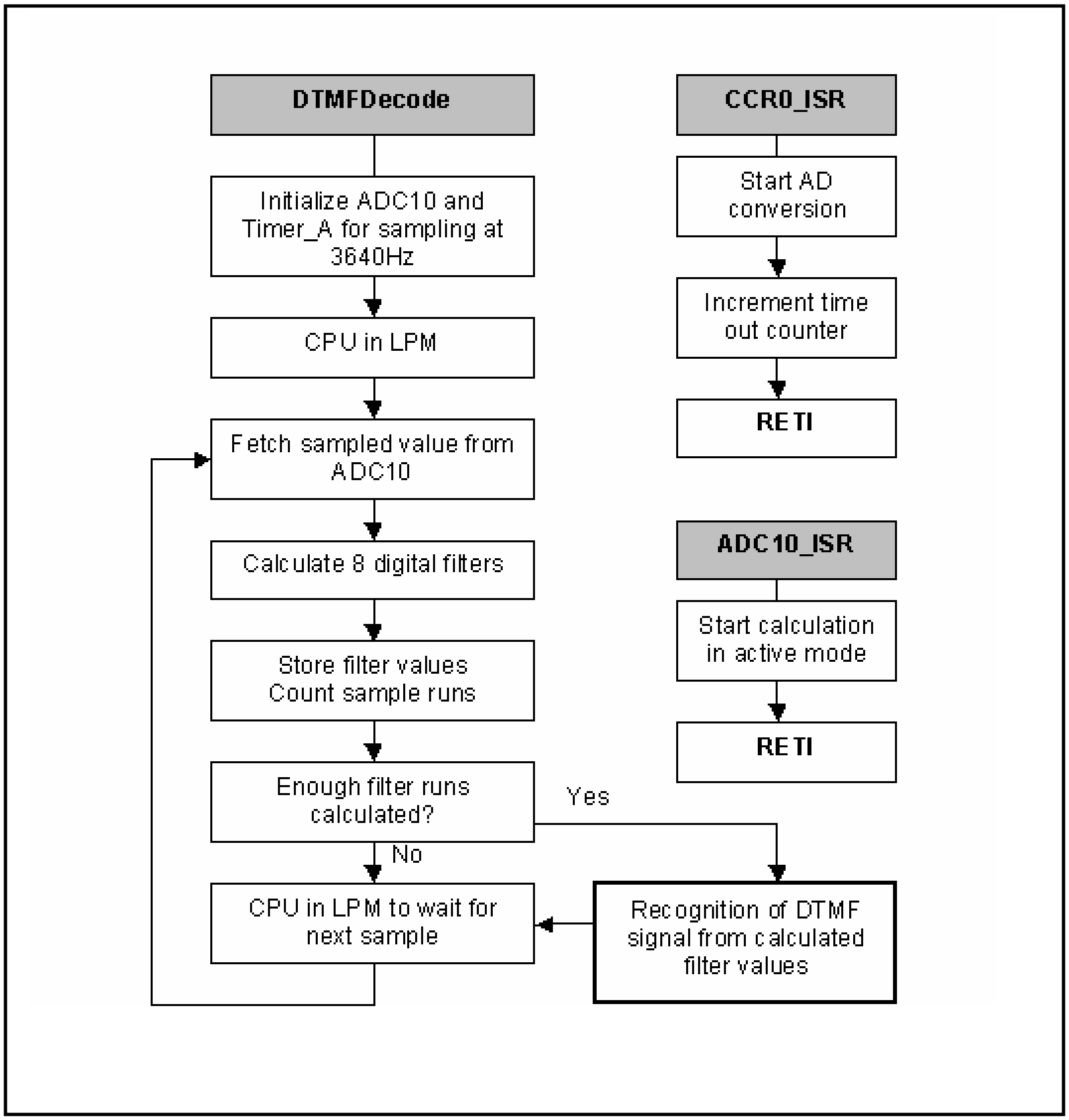
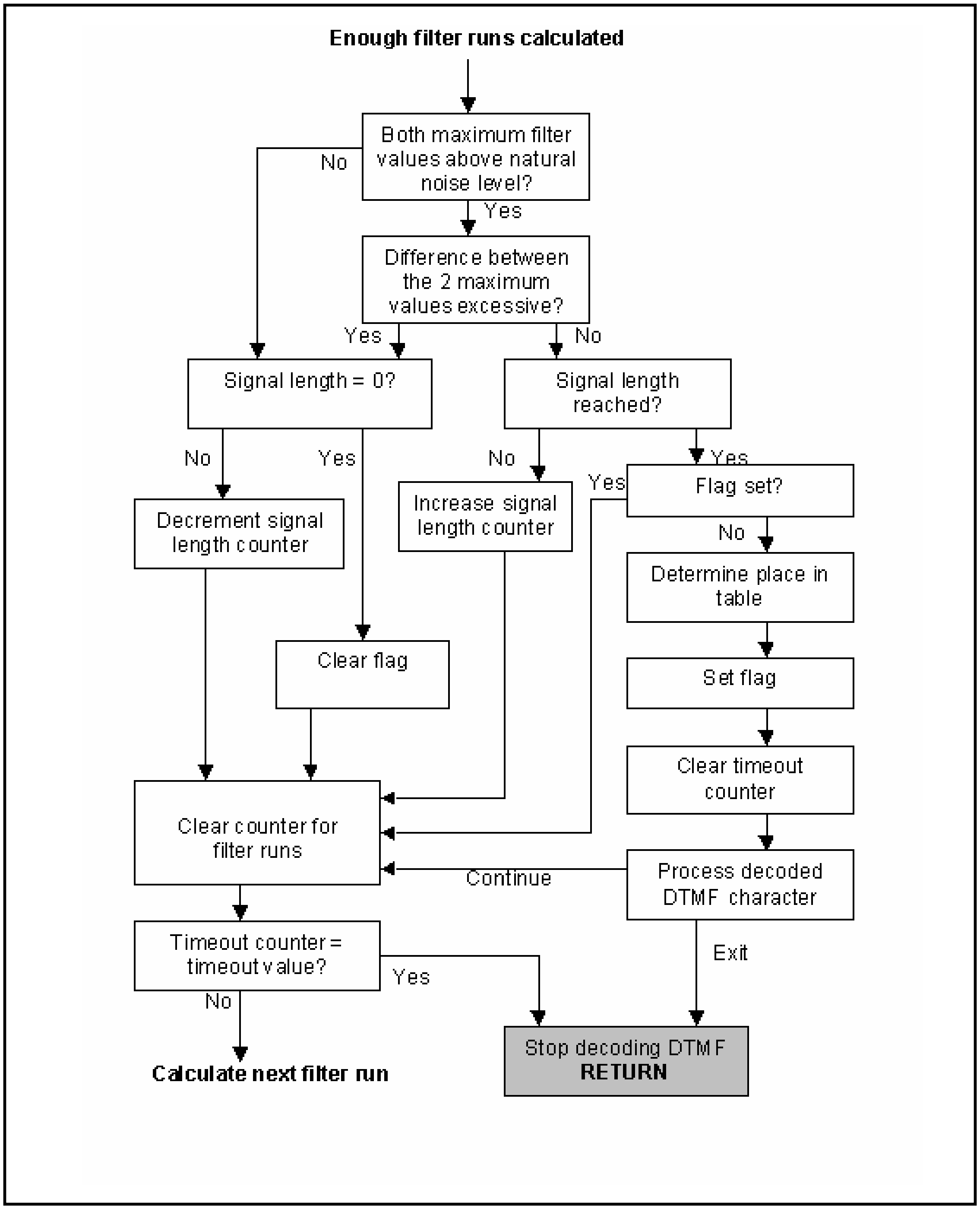


Figure 4. Recognition of DTMF from Calculated Filter Values



4.3 Password, Switch Action and Termination Command Implementation

Before calling the DTMFDecode subroutine in the main control program, an operation mode is selected by moving the constant 0 or 1 into a ModeControl variable. This selects the number of DTMF characters to decode and save in memory before returning from the subroutine.

To decode DTMF in password mode, 0 is placed in ModeControl. A sequence of four password characters is stored, which is compared to the software-programmed password upon exiting the decoding subroutine. (The password length was specified as 4 in the demonstration program, but can be changed in software.)

To decode DTMF in switch mode, a 1 is placed in ModeControl, which causes the decoding subroutine to return after storing a sequence of 2 DTMF characters. The first character should be within the range 0 through 7 to indicate which line is to be switched. A valid second character in switch mode is either a 0 (to switch the selected line OFF), or a 1 (to switch the selected line ON).

In either mode, the identification of the DTMF character */E (the termination character) results in an abrupt termination of the DTMFDecode subroutine. The character is stored at the start of the decoded DTMF sequence before returning so as to indicate to the calling program that a hang-up/termination request was received.

4.4 Timeout Functionality

The telephone-controlled switch application hangs up after 8 seconds of not receiving DTMF tones. To implement this function, a timeout counter is incremented each time the Timer_A signals the ADC10 to start a new sample. This means that the timeout counter is incremented every 0.2747 ms and the function can be implemented by executing the timeout action when the counter reaches a value of 29120 (29120 x 0.0002747 s = 7.999 s).

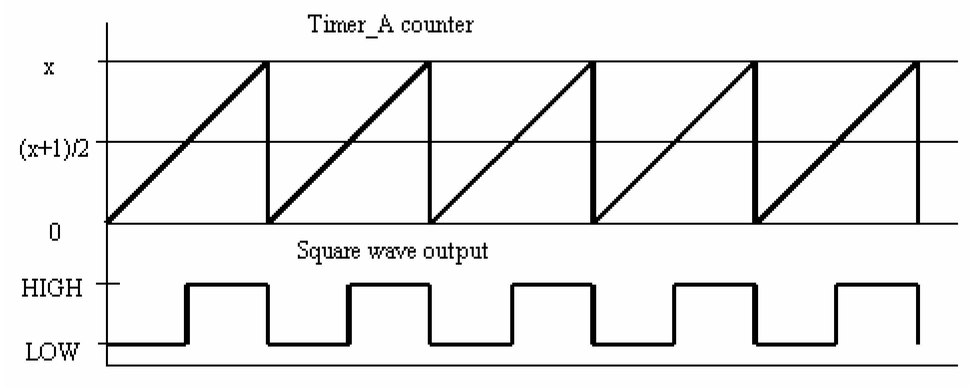
The idle-time timeout counter is cleared every time a new DTMF character is recognized. After every DTMF decoding cycle (of 20 filter calculations), the timeout counter is compared to the timeout value. If the timeout value is reached, the termination character (*/E) is stored at the beginning of the decoded DTMF sequence in memory and DTMF decoding ceases. The control program checks for this character when the DTMF decoding subroutine returns.

4.5 Audible Tone Generation

Notification tones are used to provide feedback to the user about the status of the DTMF decoder application. Two distinct notification tones within the human audible frequency range, 20 Hz to 20,000 Hz, are produced by the MSP430. The higher frequency tone is the confirmation tone. This is used for off-hook notification and to indicate that user input, such as a password sequence or a switch command sequence, is valid. The lower frequency tone is the error tone and indicates that invalid user input was received. This is also the hang-up (on-hook) notification tone.

Timer_A on the MSP430 chip is used to output a square wave of a selected frequency on P1.2 placed in output direction. This square wave is dc-filtered through capacitor C3 and passed through the secondary side of the transformer T1. (The op amp is shutdown and its outputs are placed in a high impedance mode during this process.) The signal appears on the primary side and is transmitted on the phone line to the user's earpiece where it is converted into a sound wave of the specified frequency.

Figure 5. Generating a Square Wave Using Timer_A



The 32,768-Hz auxiliary clock signal (ACLK) is selected for the Timer_A clock. To generate the higher frequency square wave (512 Hz), Timer_A counts up from 0 to 63 and then starts again from 0 (64 clock cycles). The output is set to logic high level on the 32nd count and reset to a logic low level on the 64th (on the 63 to 0 transition).

32768 Hz / 64 = 512 Hz

To generate the lower frequency square wave (128 Hz), Timer_A counts up 256 cycles of the clock. The output is set on the 128th count and reset on the 256th.

32768 Hz / 256 = 128 Hz

The Timer is stopped after the wave has been output for the required length of time.

5 How to Use the Application

1. Dial appropriate number from a phone other than the one to which the application is connected. Application responds after 5 unanswered rings and sends a confirmation tone (high pitched beep).

2. Enter password – 1 2 3 4. Confirmation tone sent out on password match; error tone (low pitched beep) sent out on mismatch.

3. After password match confirmation tone, enter digit 0 through 7 to indicate which of the 8 lines on the application you wish to switch.

4. Next, enter 0 to switch selected line OFF, or enter 1 to switch selected line ON.

5. Confirmation tone indicates valid 2-digit switch command was executed, error tone indicates invalid switch command decoded by application.

6. Cycle through steps 3, 4 and 5 as many times as necessary.

7. Can hang-up by pressing * at any time.

8. Application sends error tone and goes on-hook (hangs up) automatically after 8 seconds of silence, i.e. no key pressed, no DTMF signal received.

6 References

1. *Generation and Recognition of DTMF Signals with the Microcontroller MSP430* (SLAAE16)
2. *Texas Instruments MSP-FET430 Flash Emulation Tool (FET) User's Guide*
3. *MSP430x1xx Family User's Guide* (SLAU049B)
4. *MSP430x11x2, MSP430x12x2 Mixed Signal Microcontroller Data Sheet* (SLAS361)

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