Digital Signal Processing Lab

Experiment 3 – Dual Tone Multifrequency Encoder and Decoder Design

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Objective

- Design of bandpass digital filters
- Design of DTMF encoder and decoder
- Observing effect of noise on performance of DTMF encoder and decoder

Theory

Telephone keypads generate dual-tone multifrequency (DTMF) signals to dial a telephone number. When any key is pressed, the sinusoids of the corresponding row and column frequencies are generated and summed producing two simultaneous or dual tones. The frequencies are chosen such that no frequency is an integer multiple of other and sum or difference of two frequencies is not equal to any chosen frequency.

Table 1. ***DTMF keypad frequencies***

	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	*	0	#	D

Table 1 shows the most generally used keypad frequencies in DTMF encoding.

Encoding and Decoding

We can observe from Table 1 that each key is associated with two frequencies, lower frequency being one of the row frequencies and higher frequency being one of the column frequencies. Thus, for any given key, its encoded signal is sum of two sinusoids containing the frequencies associated with that key. For example, for 'A', possible encoded signal can be $x(t) = cos(2\pi(697)t) + cos(2\pi(1633)t)$. Decoding of the encoded signal is carried out by using digital bandpass filters. As it is claimed that any encoded signal will contain only one of the row frequencies and only one of the column frequencies, by passing the encoded signal through a bandpass filter with its centre being the frequencies used in DTMF encoding, we can compute which frequency component is present in the encoded signal. This can be done by comparing the energies of signal obtained after band passing. Maximum energy will be observed if the bandpass filter used has its centre on one of the frequencies with which the signal was encoded.

Effect of noise

If the encoded signal is corrupted with noise, then the process of decoding may fail as maximum energy could be obtained on a different frequency (if the SNR is very low) which is not used while encoding.

Design of Digital Bandpass filter

For this experiment, the bandpass filters are designed using L-point FIR filter with impulse response given as

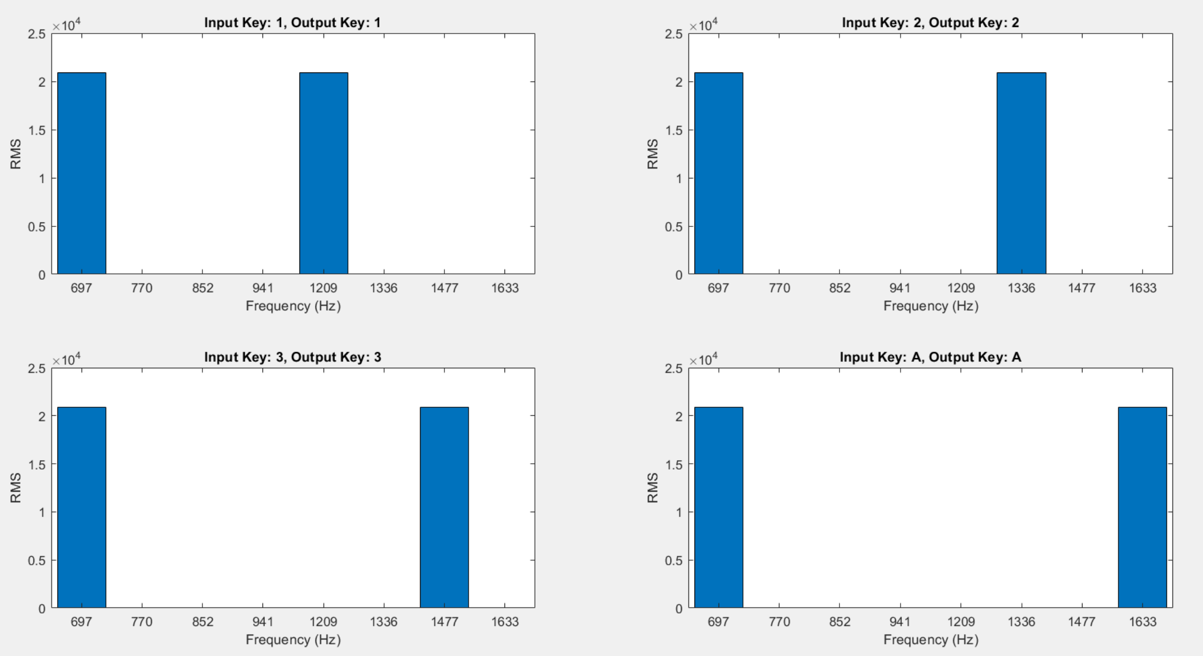
$$h(n) = \beta cos(n\omega_c); 0 \leq n < L$$

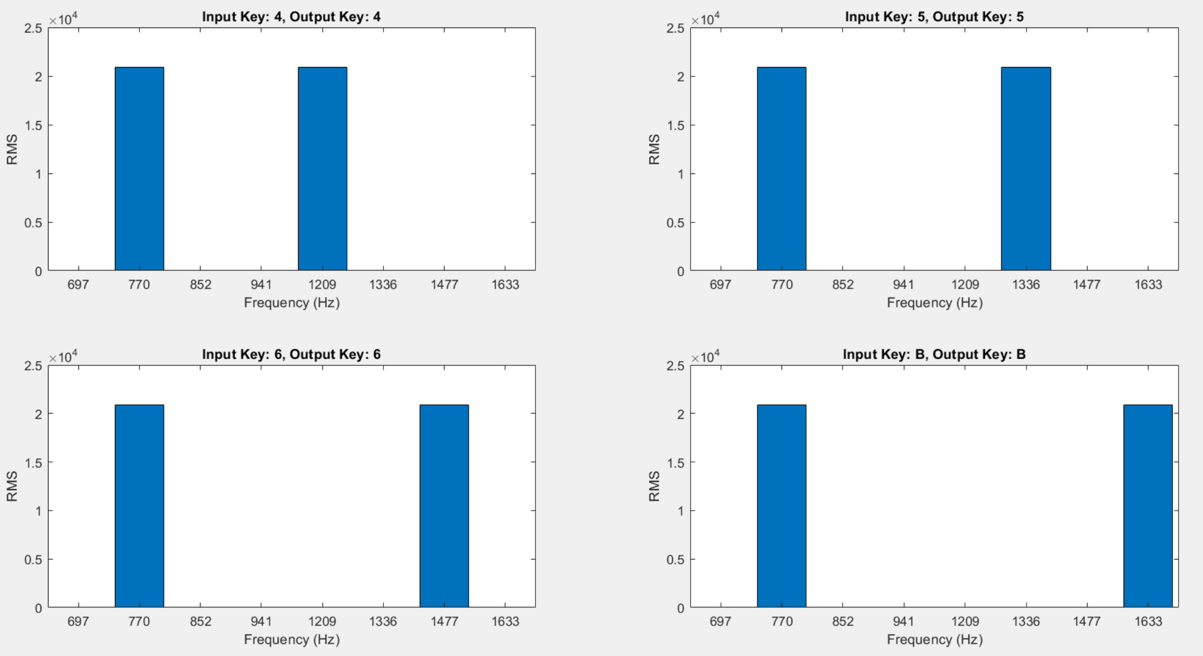
where L is the filter length, ω_c is the centre frequency that defines the frequency location of the pass band and β is used to adjust the gain in pass band. The bandwidth of the filter is controlled by L. Higher the L, narrower the bandwidth.

Results

PART A

For this part, we check the performance of DTMF encoder and decoder for each key without adding noise to the encoded signal.





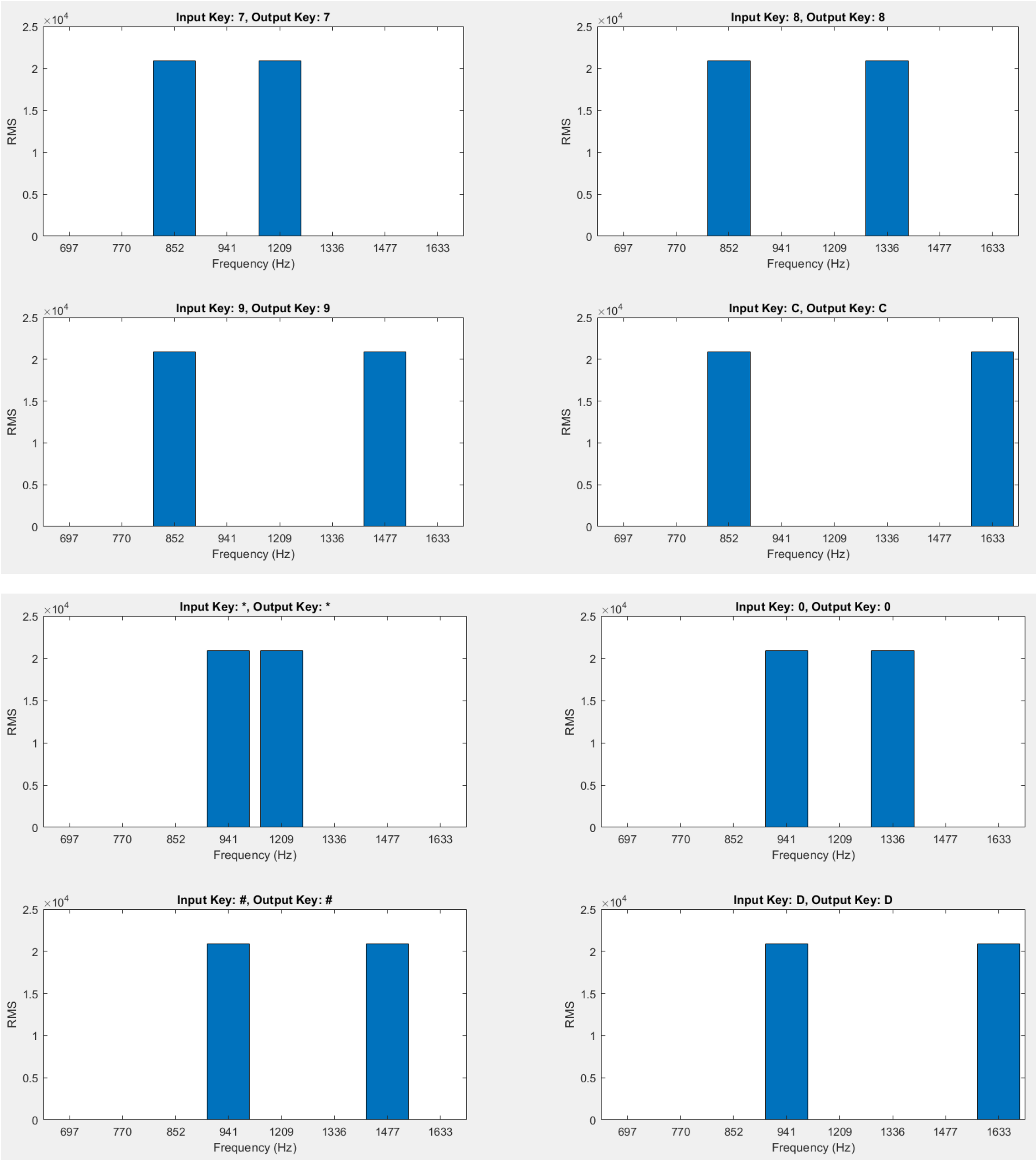


Fig. 1. ***DTMF Encoding and Decoding:*** It can be observed that for each key, the frequency used while encoding the key is correctly identified while decoding. Hence, the output key is equal to input key in all the cases. From the plots used here, Y-axis denotes the rms value of signal after being passed through bandpass filter with that frequency at its centre.

PART B

In this part of experiment, the effect of noise is observed on the performance of DTMF encoder and decoder. For simulation, the SNR was varied from 30 dB to -40 dB.

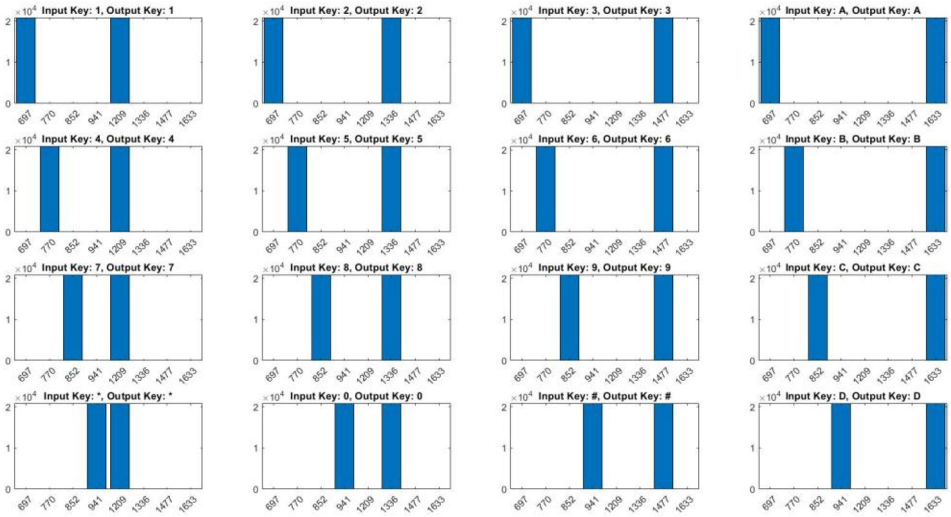


Fig. 2. ***Performance of DTMF with SNR = 30dB:*** It can be observed that for each key, the frequency used while encoding the key is correctly identified while decoding. Hence, the output key is equal to input key in all the cases. This is expected because of quite high SNR.

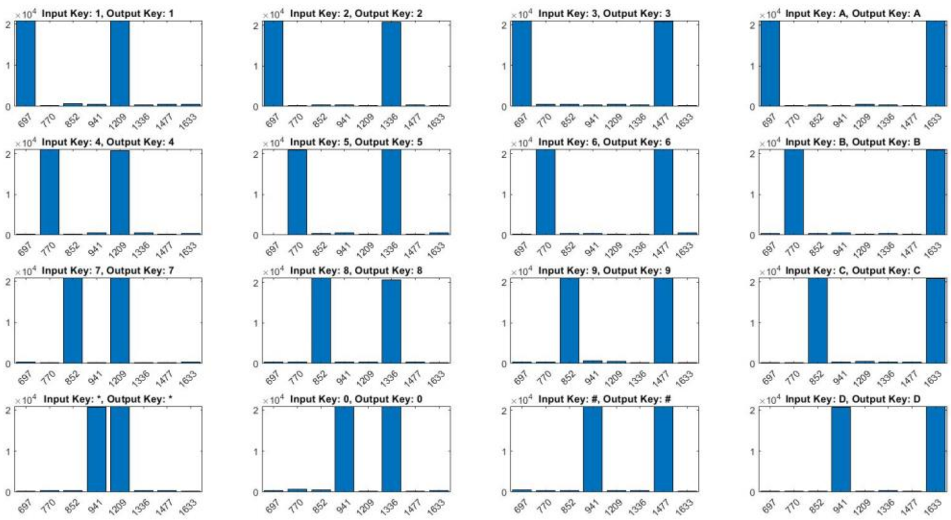


Fig. 3. ***Performance of DTMF with SNR = 0dB:*** It can be observed that for each key, the frequency used while encoding the key is correctly identified while decoding. Hence, the output key is equal to input key in all the cases. However, the components of other frequencies are non-zero because of SNR being 0 dB.

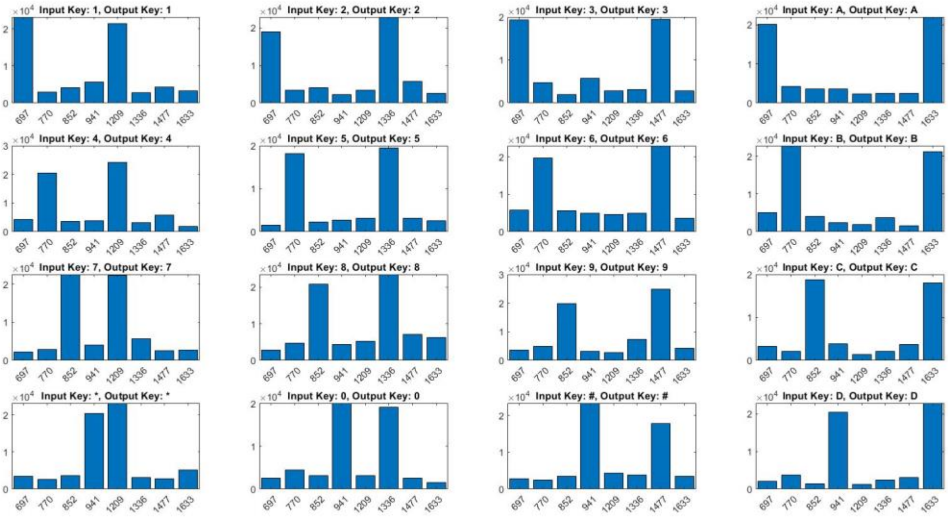


Fig. 4. ***Performance of DTMF with SNR = -20dB:*** It can be observed that for each key, the frequency used while encoding the key is correctly identified while decoding. Hence, the output key is equal to input key in all the cases. However, the components of other frequencies are also quite singnificant because of SNR being -20 dB.

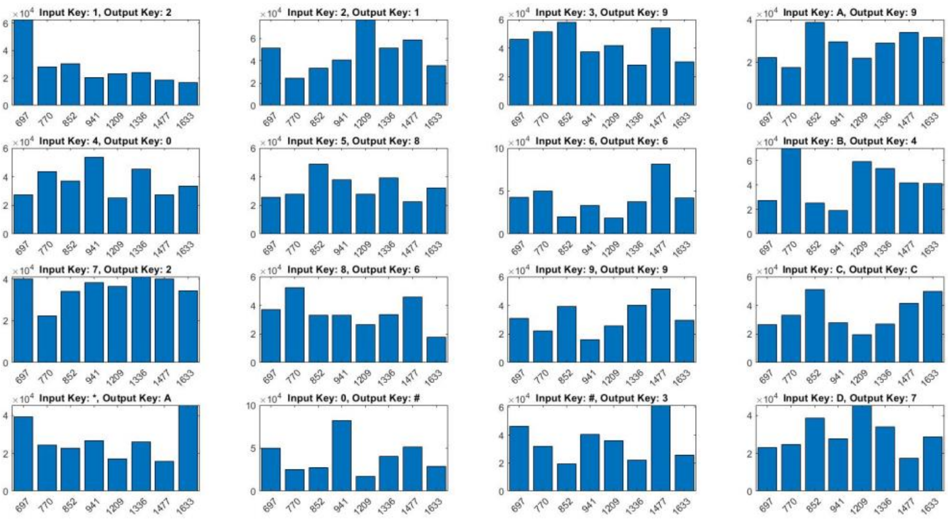


Fig. 5. ***Performance of DTMF with SNR = -40dB:*** It can be observed that for each key, the frequency used while encoding the key is **incorrectly** identified while decoding. Hence, the output key is not equal to input key in most of the cases. This is because of very low SNR, amplitudes corresponding to other frequencies (present due to noise) is higher as compared to the original frequencies used while encoding. Due to this, the decoding process fails. However, SNR of -40 dB occurs in very rare cases.

Discussion

- In this experiment, dual-tone multifrequency (DTMF) encoding and decoding technique is analysed.
- The abstract of the technique is that when, in a telephone, any key is pressed, the sinusoids of the corresponding row and column frequencies are generated and summed producing two simultaneous or dual tones.
- The frequencies are chosen such that no frequency is an integer multiple of other and sum or difference of two frequencies is not equal to any chosen frequency.
- Each key is associated with two frequencies, lower frequency being one of the row frequencies and higher frequency being one of the column frequencies.
- Decoding of the encoded signal is carried out by using digital bandpass filters.
- As it is claimed that any encoded signal will contain only one of the row frequencies and only one of the column frequencies, by passing the encoded signal through a bandpass filter with its centre being the frequencies used in DTMF encoding, we can compute which frequency component is present in the encoded signal.
- This can be done by comparing the energies of signal obtained after band passing. Maximum energy will be observed if the bandpass filter used has its centre on one of the frequencies with which the signal was encoded.
- From Fig. 1, it can be observed that for each input key, the frequencies used while encoding have been correctly identified while decoding, thus being a successful encoder-decoder procedure.
- In the second part of the experiment, the effect of noise on performance of DTMF encoder and decoder is analysed.
- From Fig. 2, 3, 4 and 5, it can be observed that DTMF encoder and decoders work very well until SNR becomes -40 dB, where the algorithm used for decoding fails. However, in real cases, SNR of -40 dB is never observed. Thus, it can be concluded that DTMF encoder and decoder algorithm can be used in wide varieties of signal processing tasks.

Appendix

MATLAB Codes

```
% Author: Utkarsh Patel (18EC30048)
% Experiment 3 - Encoding and decoding using bandpass filters

M = ['1' ,'2' ,'3' ,'A' ; '4', '5', '6', 'B'; '7', '8', '9', 'C'; '*', '0', '#', 'D']; % Available keys
X = categorical({'697', '770', '852', '941', '1209', '1336', '1477', '1633'});         % Encoding frequencies
X = reordercats(X, {'697', '770', '852', '941', '1209', '1336', '1477', '1633'});

SNR = 30; % SNR of encoded signal

for i = 1: 4
    for j = 1: 4
        input_key = M(i, j);
        x = Encode(input_key); % Encoding
        noizz = randn(size(x)) * std(x) / db2mag(SNR);
        x = x + noizz;
        [output_key, RMS] = Decode(x); % Decoding
        subplot(4, 4, 4 * (i - 1) + j);
        bar(X, RMS);
        xlabel("Frequency (Hz)");
        ylabel("RMS");
        title("Input Key: " + string(input_key) + ", Output Key: " + string(output_key));
    end
end


function [key, RMS] = Decode(x)
% Returns the key after decoding the signal 'x'
    M = ['1' ,'2' ,'3' ,'A' ; '4', '5', '6', 'B'; '7', '8', '9', 'C'; '*', '0', '#', 'D']; % list of available keys
    freq_col = [1209, 1336, 1477, 1633]; % Encoding frequency as per the column
    freq_row = [697, 770, 852, 941];     % Encoding frequency as per the row
    Fs = 4000; % Sampling frequency
    N = 2048 * 10;

    RMS = zeros(1, 8);

    row = 0; % to-be-decoded row index of key
    col = 0; % to-be-decoded col index of key
    rowmax = 0; % maximum of the energies of freq in freq_row in encoded signal x
    colmax = 0; % maximum of the energies of freq in freq_col in encoded signal x

    % Decoding the row index of key from x
    for i = 1: 4
        fil = BPFil(N, 5, freq_row(i) / Fs); % bandpass filter
        y = conv(fil, x);
        RMS(i) = rms(y);
        if rms(y) > rowmax
            rowmax = rms(y);
            row = i;
        end
    end

    % Decoding the col index of key from x
    for i = 1: 4
        fil = BPFil(N, 5, freq_col(i) / Fs); % bandpass filter
        y = conv(fil, x);
        RMS(4 + i) = rms(y);
        if rms(y) > colmax
            colmax = rms(y);
            col = i;
        end
    end

    key = M(row, col);
end



function x = Encode(key)
% Returns the encoded signal for passed key
    M = ['1' ,'2' ,'3' ,'A' ; '4', '5', '6', 'B'; '7', '8', '9', 'C'; '*', '0', '#', 'D']; % list of available keys
    freq_col = [1209, 1336, 1477, 1633]; % Encoding frequency as per the column
    freq_row = [697, 770, 852, 941];     % Encoding frequency as per the row
    Fs = 4000; % Sampling frequency
    N = 2048 * 10;
    t = 0: 1 / Fs: (N - 1) / Fs; % time range
    x = 0;
    for i = 1: 4
        for j = 1: 4
            if M(i, j) == key
                x = cos(2 * pi * freq_row(i) * t) + cos(2 * pi * freq_col(j) * t);
            end
        end
    end
end


function fil = BPFil(N, b, wc)
% Bandpass filter design
    fil = zeros(1, N);
    for i = 0: N - 1
        fil(i + 1) = b * cos(2 * pi * wc * i);
    end
end
```