Design of a Wireless Data Transmission Protocol for Underwater Acoustic Networks

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Abstract: In the present world underwater acoustic sensor network (UWSN) is a new research area and currently quite challenging in terms of limited bandwidth, low data rates and multipath propagation & high equipment costs. Most of the research works are stalled by some fundamental factors. For example, high cost of underwater networking experiments as well as lack of portable devices to conduct experiments. In this paper, a new underwater data transmission protocol is proposed to promote experimental research works and to form an underwater acoustic sensor network in which data is transmitted by DTMF tones. The total system consists of a portable transmitter and a receiver. On the transmission module user input will be encoded into DTMF tones, and these tones are generated automatically using a microcontroller. The tone signal is modulated and then transmitted via an acoustic transmitter in form of acoustic waves. On the receiver module these acoustic waves are received via low cost hydrophones which have the ability to capture sound signal in underwater condition. The received signal is decoded into digital binary digits using a DTMF decoder. The decoded digits are combined and the corresponding ASCII character is shown. This portable device can be operated using battery as low power is required to transmit data. The system requires very low power and hence ensures longer battery life.

Keywords: Acoustic signals, Underwater Acoustic Sensors, DTMF, Hydrophones, and Frequency Modulation.

Introduction: Underwater Sensor Network (UWSN) has been of growing interest in recent years. UWSNs are promising to monitor pollution, provide an early warning for natural disasters like Tsunami, applications for defense purposes, and assist in finding and recovering wrecked aircrafts or ships. Underwater sensor network requires wireless communication system to transfer data and in the present era acoustic signals are most efficient in underwater condition as sound travels at 1450ms^{-1}-1500 ms^{-1}. Electromagnetic signals are mostly distorted and not efficient in underwater condition for transmitting information over long distances. Underwater data transmission systems are facing some difficulties in terms of limited bandwidth, slow data rates and multipath propagation. To overcome these factors different MAC protocols and Physical layer techniques have been proposed. Desert star SAM1 acoustic modem (Desert Star Systems) costs around ~$2600 USD and covers up to 300 meter with operating frequency 38 KHz-42 KHz. This device is not affordable for students to use this device for research purpose. In other research works an underwater acoustics modem was designed (B. Benson et al 2010) for short range sensor networks. The modulation and demodulation were performed using high cost FGPA boards which are not quite affordable. Kaizhuo Lei (et al. 2008) implemented underwater acoustic transmitter with FPGA board and used complex modulation technique like OFDM. To control stepper motor with remote DTMF (Dual tone Multiple Frequency) tones were used (Yun Chan Cho. et al. 2008). D. Manojkumar (et al. 2010) has controlled a robot by a mobile using DTMF tone. To control domestic systems DTMF has been used (Tulijappa M Ladwa et al. 2008). Smart phones also have been used to control mobile robots (Daniel H. et al. 2009). Md. Khaled Hossain (et al. 2013) used DTMF tones collect sensor data to measure CO_2 & humidity. In this paper work, a new wireless data transmission protocol for underwater communication has been proposed, where data is transmitted by DTMF tones in form of acoustic signal in underwater condition using simple frequency modulation technique. Furthermore using DTMF tone complete ASCII chart has been implemented. From transmission side the user input or sensor data will be encoded into DTMF tones and transmitted via acoustic transmitter. On the Receiver side this DTMF tone will be decode into digital binary values and combining two DTMF tones will represent its corresponding ASCII character. This tone technology is very much efficient in underwater communication as acoustic signals travels much faster in water and covers longer distance and consumes low power. Frequency modulation is used, so other surrounding noises can not put high impact on the message signal. The transmitter and receiver module has been shown separately, but it can be used as transceiver. This prototype consumes a low power and can be used for different underwater research purposes.

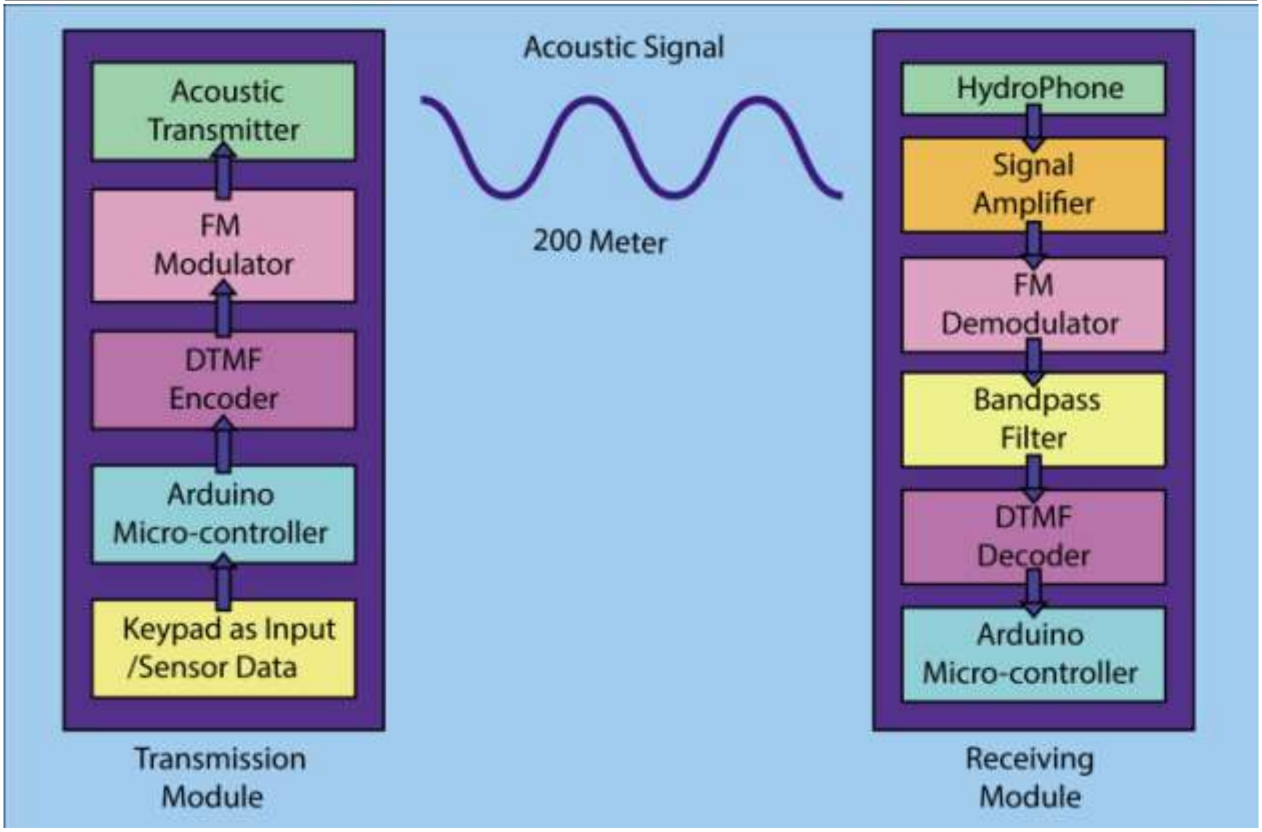


Fig. 1: Basic Project Outline

1. Basic Project Outline:

1.1) **Transmission Module**: In the above figure overall project diagram is shown. The brain of this prototype is Arduino Micro-controller. This prototype consists of two modules. One is transmission and another is receiving module. On the transmission side the input signal is processed through different steps. There are two ways to give input in the Micro-controller. Any type of sensor can be interfaced with microcontroller and the data can be automatically converted into DTMF tones. Another way of giving input is manual keypad input. Every digit consists of two Hexa decimal characters. In order to insert a letter users have to dial two Hexa decimal characters which represent the corresponding value of the letter. For example, if the users want to insert letter “H” then he has to press 4 & 8. Microcontroller takes this input and generates corresponding DTMF tones. This tone is processed through the FM modulator to add carrier signal. The range of DTMF tones are 1.96 KHz-2.57 KHz. The carrier frequency can be varied from 10 KHz to 1 MHz .This modulated signal is passed through the acoustic transmitter in underwater.

1.2) Receiving module: On the receiving module the hydrophone is used to capture the acoustic signal. As the transmitted signal travels a long distance, in the first stage the received signal is amplified using a power amplifier. In the following stage the amplified signal is demodulated using FM demodulator to separate the message signal from carrier signal. The hydrophones capture some noise signal from its surrounding, as like sound produced by fish, or ships using sound waves to measure height etc. So some noise exists in the demodulated signal and the signal is distorted. A butterworth band pass filter is used to separate the message signal from the noisy signal. After this process the message signal is passed through the DTMF decoder and converted into digital binary bits. Then these binary bits are converted in ASCII values by the micro-controller.

2. Circuit Analysis:

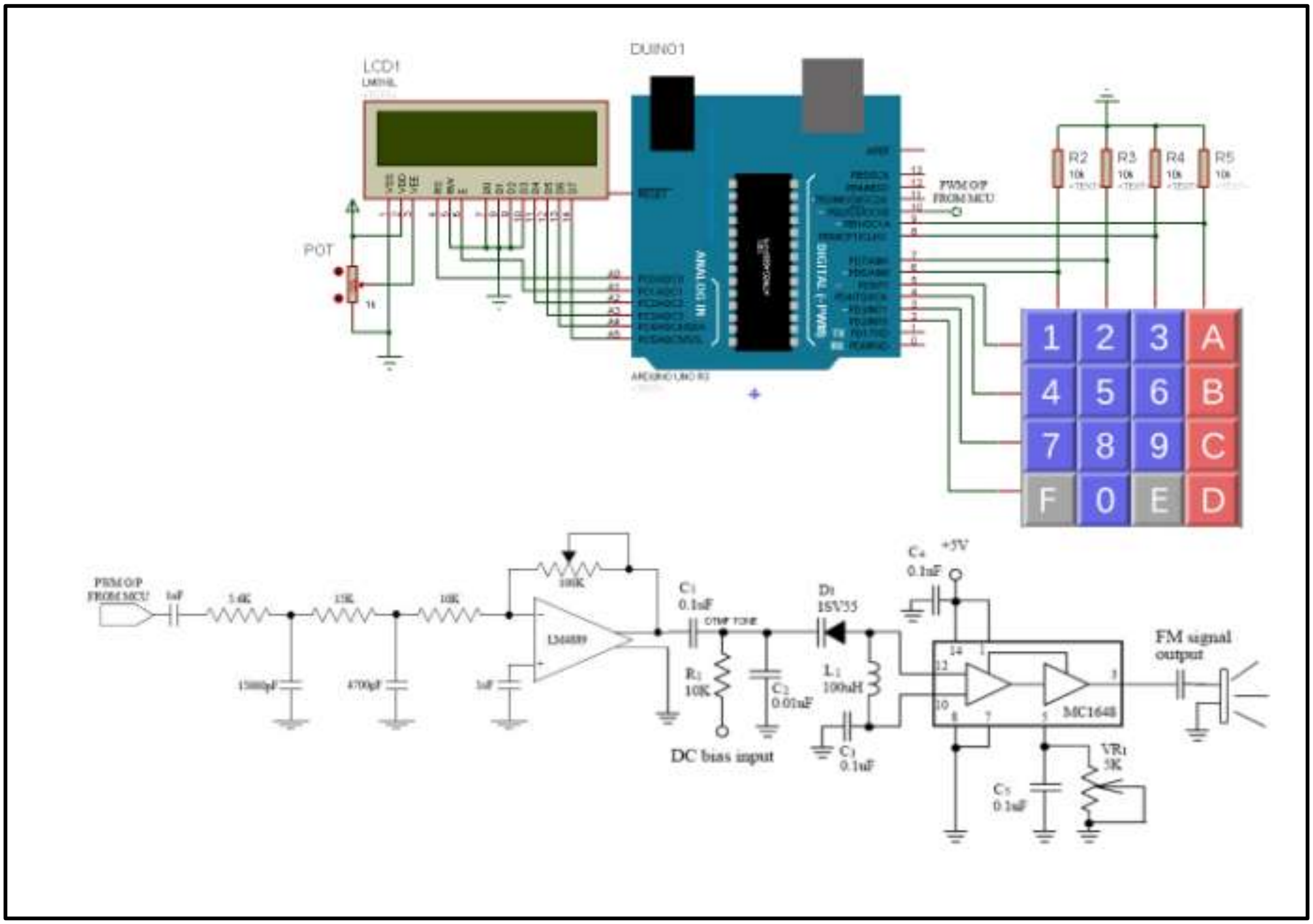


Fig. 2: Transmission Module

2.1) **Transmission Module:** Key feature of the transmission side is generating DTMF tones using microcontroller. DTMF stands for Dual-Tone Multiple frequency. From Figure 4, the row represents the lower frequency and column represents the higher frequency values. For example, the matrix in the figure 4 shows that the digit 4 is represented by low frequency 770 Hz and a high frequency of 1209 Hz. The two frequencies are transferred to a DTMF signal using the following equation:

$$f(t) = A_a \sin(2\pi f_a t) + A_b \sin(2\pi f_b t)$$

Where the ratio between the two amplitudes should be:

$$A_b/A_a = K \qquad 0.7 < K < 0.9$$

A sine wave can be generated if the average voltage generated by the PWM is changed in every PWM cycle. The relation between high and low level has to be attuned according to the voltage level of the sine wave at the respective time. The values for adjusting the PWM can be calculated every PWM cycle or stored in a lookup table (LUT). The code of lookup tables are given below.

```
//Order of dtmf are : 0123456789 * #
const int DTMF_freq1[] = { 1336, 1209, 1336, 1477, 1209, 1336, 1477, 1209, 1336, 1477,1209 ,1477  };
const int DTMF_freq2[] = {  941,  697,  697,  697,  770,  770,  770,  852,  852,  852, 941 ,941   };
```

The PWM signal is put out on the OC1A. An additional output filter will help to achieve a good sinusoid. If the PWM frequency is decreased, it can be necessary to implement a steeper filter to obtain a good result. DTMF tones are generated with the help of Tone.h library. DTMF tones are combination of two frequencies in order to generate DTMF tone microcontroller generates two PWM signals on pin 10 & 11. Code of generating DTMF tones shown below:

```
void playDTMF(uint8_t number, long duration)
{
  freq1.play(DTMF_freq1[number], duration);
  freq2.play(DTMF_freq2[number], duration);
}
```

For example if we want to insert letter “H”, we need DTMF tones 4 & 8. At first stage these two digits are separated by diving by 10 & reminder by 10. The following code generates these two tones:

```
playDTMF(4,400);
playDTMF(8,400);
```

These generated tones are converted into sinusoidal signals through LM4889 IC. In the following step these signals are passed through the frequency modulator for modulation choosing carrier frequency 50 KHz and sampling frequency 8 KHz. Then the signal transmitted via Benthowave acoustic transmitter BII-8030 in underwater.

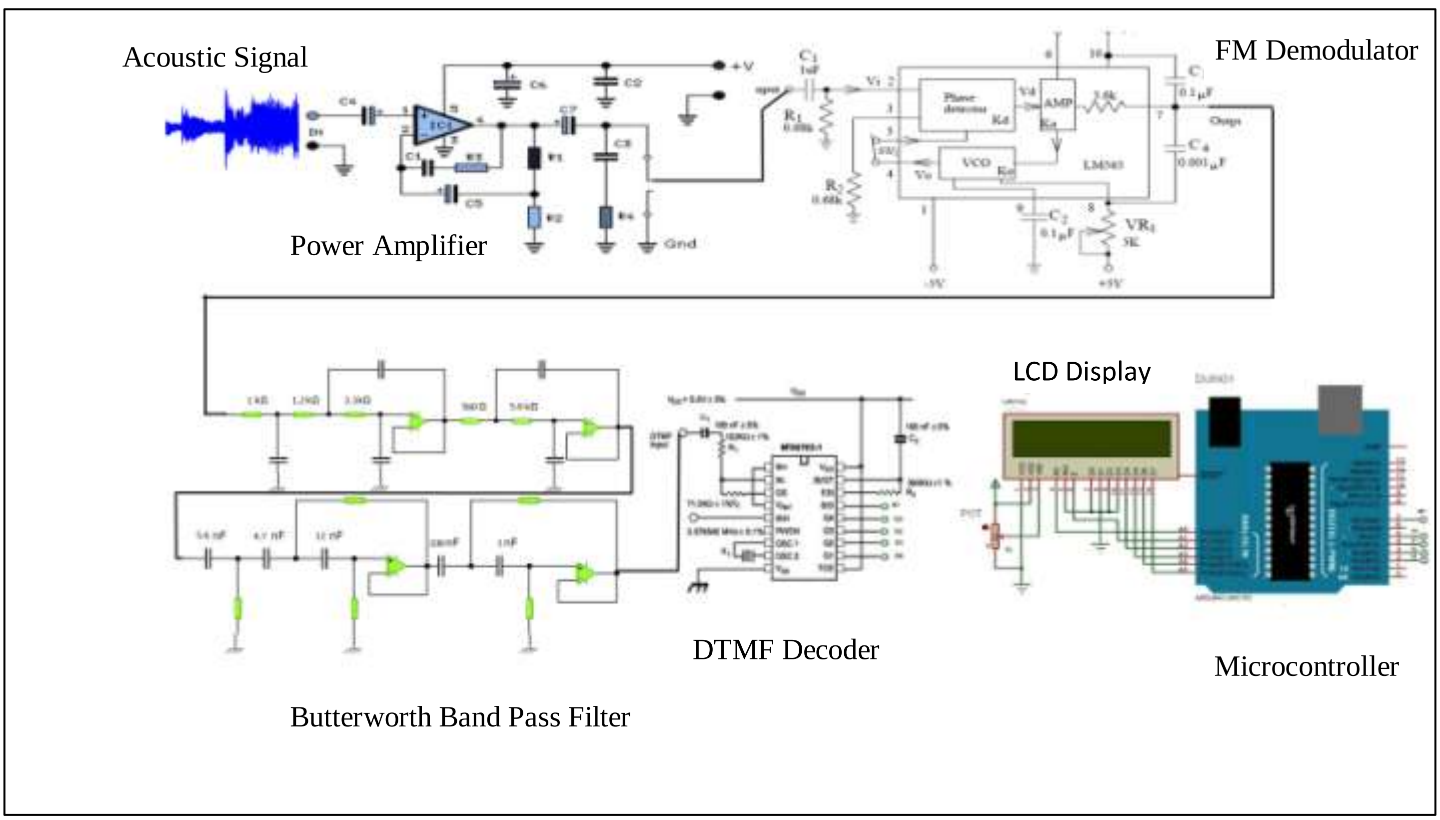


Fig. 3 : Receiver Module

2.2) Receiver Module: The transmitted acoustic signal is received by a hydrophone which can receive signal ranged from 10 KHz-1 MHz. As the received signal strength is weak due to long distance travel, at first stage the signal is amplified using a power amplifier. The amplified signal is demodulated using the frequency demodulator to separate the message signal from the carrier signal. Now the demodulated signal consists some noise signal as hydrophone receives some noise from its surroundings. The demodulated signal is distorted due to some noise so a butterworth band pass filter is used to remove the noise from the message signal. Then this message signal is passed through the MT8870D DTMF decoder input pin to decode the DTMF tone to its corresponding binary bits. The Q1, Q2, Q3, Q4 pins of MT8870D DTMF decoder are connected to the pin number 5,4,3,2 of the microcontroller. In order to generate a letter Microcontroller detects two successive DTMF tones and combine them. For Letter "H" the corresponding DTMF tone is 0X48. The first DTMF tone for digit 4 creates binary values for D_0= 0, D_1=0 D_2=1 D_4=0 and for digit 8 only D_3 is high and rest of the bits are low. In this process the receiver module receives data.

3) Main Technology Used:

3.1) DTMF TONE

DTMF generation is a composite sinusoidal signal of two tones between the frequencies ranging from 697Hz to 1633Hz (CAT Paper). The DTMF keypad is arranged in a particular way that each row represents its own unique tone frequency and also each column represents its own unique tone. Below is a representation of the typical DTMF keypad and the associated row/column frequencies.

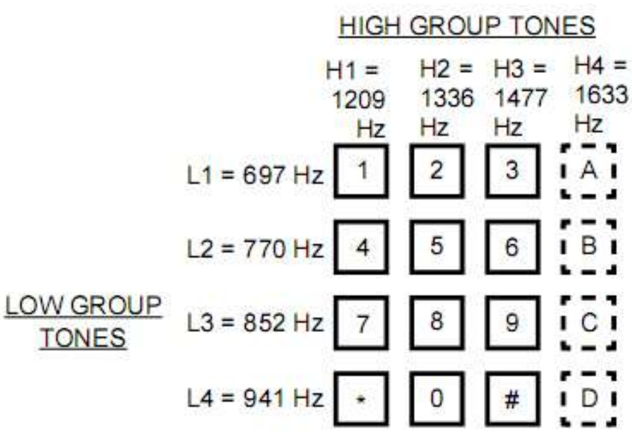


Fig. 4 : DTMF Keypad layout

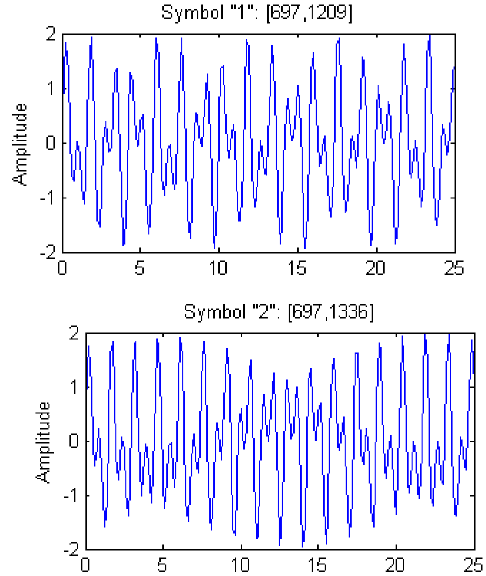


Fig. 5: DTMF frequency when any digit is pressed

3.2) Our Software defined DTMF Keypad

F_{LOW}	F_{HIGH}	KEY	TOE	Q_4	Q_3	Q_2	Q_1
697	1209	1	1	0	0	0	1
697	1336	2	1	0	0	1	0
697	1477	3	1	0	0	1	1
770	1209	4	1	0	1	0	0
770	1336	5	1	0	1	0	1
770	1477	6	1	0	1	1	0
852	1209	7	1	0	1	1	1
852	1336	8	1	0	0	0	0
852	1477	9	1	1	0	0	1
941	1209	0	1	1	0	1	0
941	1336	*	1	1	0	1	1
941	1477	#	1	1	1	0	0
697	1633	A	1	1	1	0	1
770	1633	B	1	1	1	1	0
852	1633	C	1	1	1	1	1
941	1633	D	1	0	0	0	0
-	-	ANY	0	Z	Z	Z	Z

Table 1: Original DTMF Tone Matrix Table

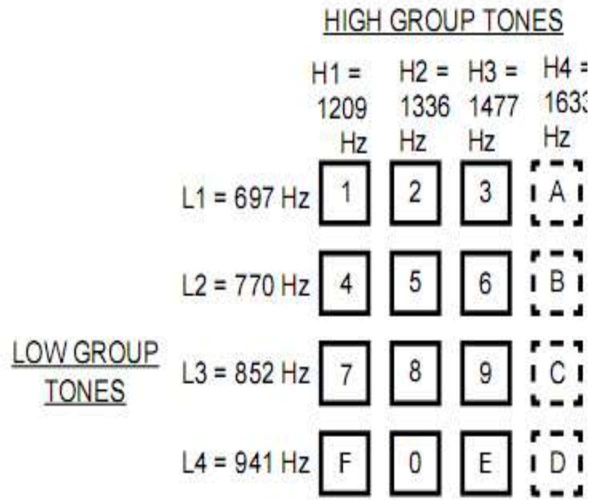


Fig. 6: DTMF keypad with digits E, F

In our work we have eliminated * & # button and added E & F button. Now this keypad contains all 16 digits of BCD (binary coded decimal) digits. We have also changed the table value of DTMF tones according to BCD values. The chart bellow represents the values of all 16 digits. Microcontroller receives original DTMF value but it converts the original value into the above value using look up table. To form an ASCII character we need two BCD digits. To represent any digit two DTMF tones needed to be sent. For Example if user wants to send a character ‘H’ it will send DTMF tones 4 & 8 as the hex value of ‘H’ is 0x48. In this way sensors can send any character it wants from ASCII table. Bellow we have shown the ASCII chart and corresponding DTMF tones in red color. If user wants to transmit a data like example, “Hello” to the receiver it has to send the following DTMF tones. To cover all the ASCII characters the new keypad follows the following truth table.

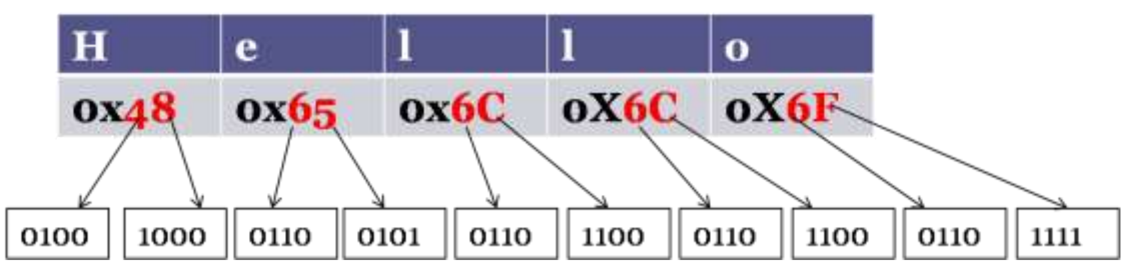
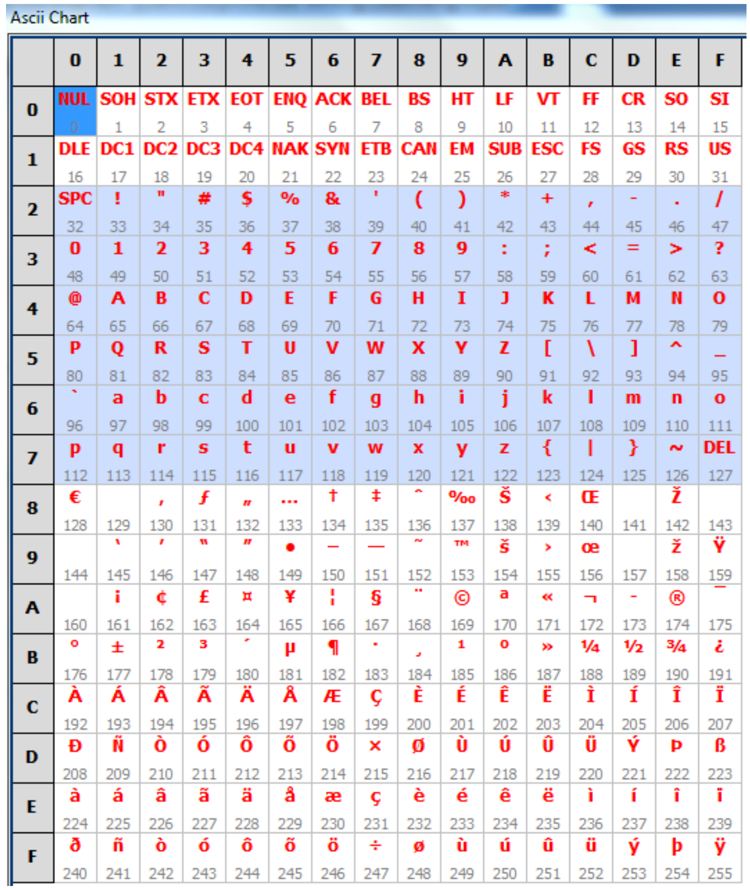


Fig.7: DTMF tones for the word “HELLO”

KEY	TOE	Q4	Q3	Q2	Q1
0	1	0	0	0	0
1	1	0	0	0	1
2	1	0	0	1	0
3	1	0	0	1	1
4	1	0	1	0	0
5	1	0	1	0	1
6	1	0	1	1	0
7	1	0	1	1	1
8	1	0	0	0	0
9	1	1	0	0	1
A	1	1	0	1	0
B	1	1	0	1	1
C	1	1	1	0	0
D	1	1	1	0	1
E	1	1	1	1	0
F	1	1	1	1	1
ANY	0	Z	Z	Z	Z

Table 2: Software Defined DTMF tone values


Ascii Chart

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	NUL 0	SOH 1	STX 2	ETX 3	EOT 4	ENQ 5	ACK 6	BEL 7	BS 8	HT 9	LF 10	VT 11	FF 12	CR 13	SO 14	SI 15
1	DLE 16	DC1 17	DC2 18	DC3 19	DC4 20	NAK 21	SYN 22	ETB 23	CAN 24	EM 25	SUB 26	ESC 27	FS 28	GS 29	RS 30	US 31
2	SPC 32	! 33	" 34	# 35	$ 36	% 37	& 38	' 39	(40	) 41	* 42	+ 43	, 44	- 45	. 46	/ 47
3	0 48	1 49	2 50	3 51	4 52	5 53	6 54	7 55	8 56	9 57	: 58	; 59	< 60	= 61	> 62	? 63
4	@ 64	A 65	B 66	C 67	D 68	E 69	F 70	G 71	H 72	I 73	J 74	K 75	L 76	M 77	N 78	O 79
5	P 80	Q 81	R 82	S 83	T 84	U 85	V 86	W 87	X 88	Y 89	Z 90	[91	\ 92	] 93	^ 94	_ 95
6	` 96	a 97	b 98	c 99	d 100	e 101	f 102	g 103	h 104	i 105	j 106	k 107	l 108	m 109	n 110	o 111
7	p 112	q 113	r 114	s 115	t 116	u 117	v 118	w 119	x 120	y 121	z 122	{ 123	| 124	} 125	~ 126	DEL 127
8	€ 128	129	‚ 130	ƒ 131	„ 132	… 133	† 134	‡ 135	ˆ 136	‰ 137	Š 138	‹ 139	Œ 140	141	Ž 142	143
9	144	‘ 145	’ 146	“ 147	” 148	• 149	– 150	— 151	˜ 152	™ 153	š 154	› 155	œ 156	157	ž 158	Ÿ 159
A	160	¡ 161	¢ 162	£ 163	¤ 164	¥ 165	¦ 166	§ 167	¨ 168	© 169	ª 170	« 171	¬ 172	- 173	® 174	¯ 175
B	° 176	± 177	² 178	³ 179	´ 180	µ 181	¶ 182	· 183	¸ 184	¹ 185	º 186	» 187	¼ 188	½ 189	¾ 190	¿ 191
C	À 192	Á 193	Â 194	Ã 195	Ä 196	Å 197	Æ 198	Ç 199	È 200	É 201	Ê 202	Ë 203	Ì 204	Í 205	Î 206	Ï 207
D	Ð 208	Ñ 209	Ò 210	Ó 211	Ô 212	Õ 213	Ö 214	× 215	Ø 216	Ù 217	Ú 218	Û 219	Ü 220	Ý 221	Þ 222	ß 223
E	à 224	á 225	â 226	ã 227	ä 228	å 229	æ 230	ç 231	è 232	é 233	ê 234	ë 235	ì 236	í 237	î 238	ï 239
F	ð 240	ñ 241	ò 242	ó 243	ô 244	õ 245	ö 246	÷ 247	ø 248	ù 249	ú 250	û 251	ü 252	ý 253	þ 254	ÿ 255

Fig.8: Complete ASCII chart using DTMF tones only

To send the character “H” two DTMF tones are 4 & 8 are required. At the receiver end the received DTMF tone is decoded to digital binary values and combined together to show the corresponding ASCII character “H”

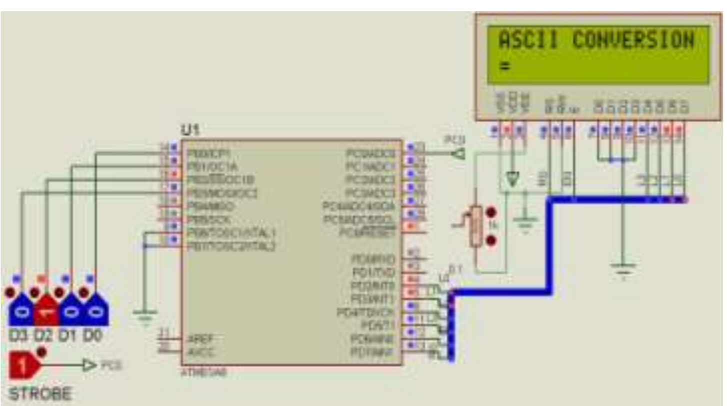


Fig. 9: The First tone “4” is decoded to digital value 0100

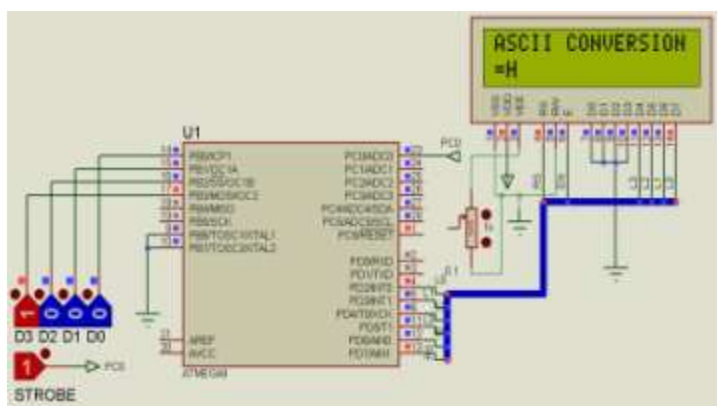


Fig.10: The second tone is decoded, combined & Character “H” shown

4) Modulation Performance Analysis:

Different types of Modulation techniques are used for underwater acoustic communication like OFDM, FSK etc. In this research work as DTMF tones (Analog Signals) are used to transmit data, so simple frequency modulation technique is used for modulation and the performance is analyzed. In Fig 11 a random DTMF tone "E" has been taken as input. The frequency of tone E [941, 1209]. The next figure represents the frequency estimation of the tone E. The frequency combination of E is 2.15 KHz and is modulated using a carrier signal.

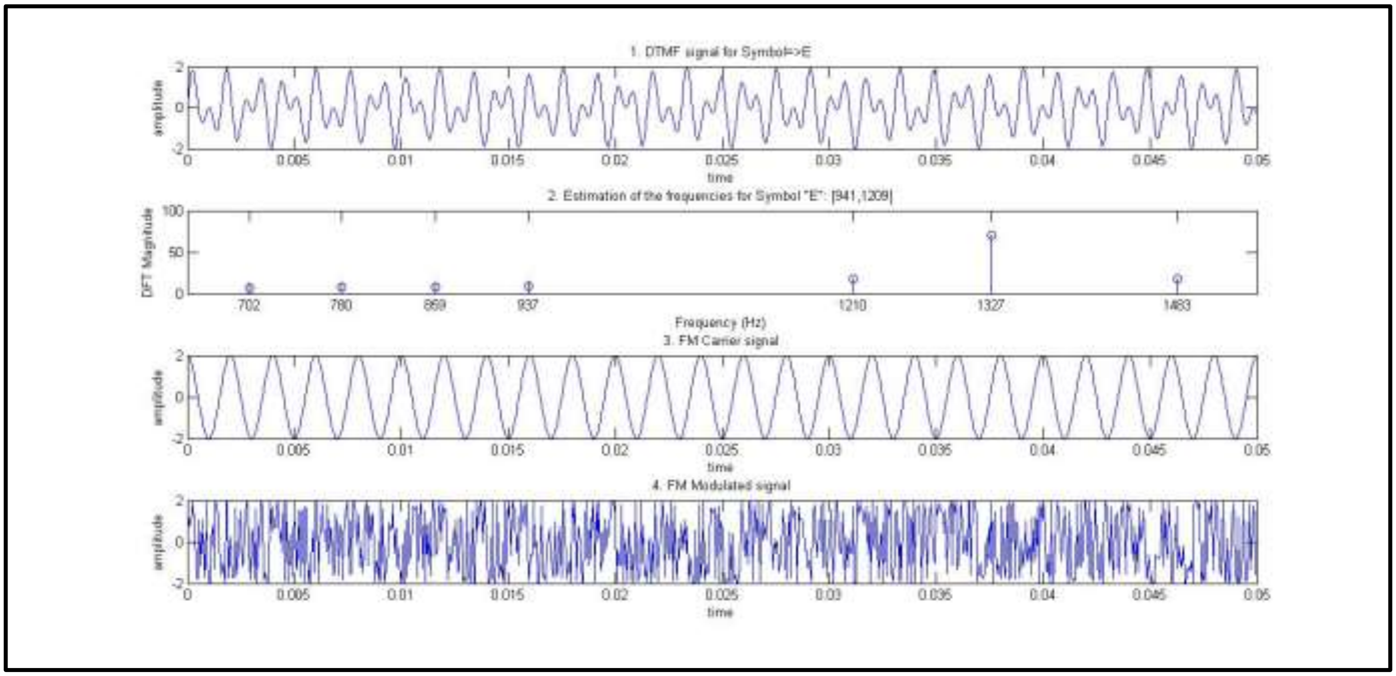


Fig.11: Modulation of the DTMF tone E

After receiving the modulated signal, the signal has been demodulated at the receiver end and was filtered to separate the message signal from the noise. We can see on the figure 12 that after filtering the massage signals frequency estimation changed in a few points of the frequency. By comparing the input signal and the final output signal at the receiver end we can see the percentage error presentation, which represents some small deviation in the received message signal

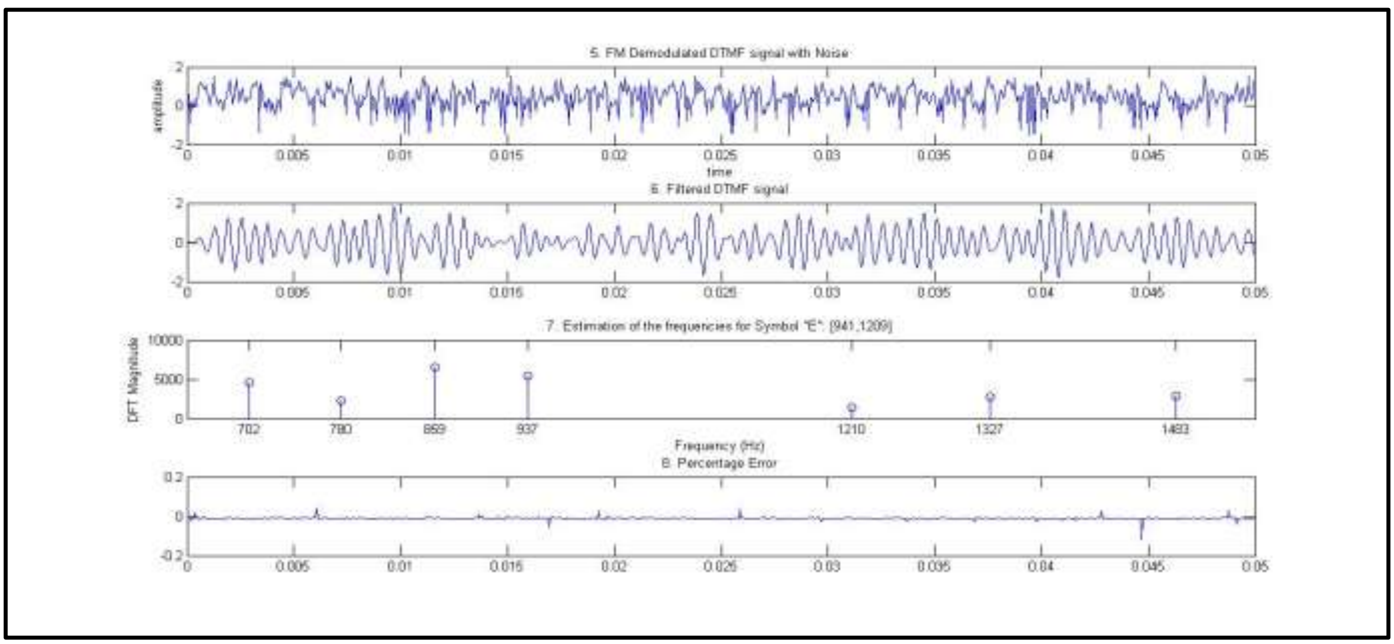


Figure 12: Demodulated and filtered Message signal E

5) Future Works:

This simple wireless transmission protocol can be used for detecting objects using sensors, for robots community development and intelligence sharing, wireless robot control, long distance data communication etc. Apart from this, the device can be used as an acoustic modem to transmit huge amount of data and to create a wide underwater sensor networks.

6) Conclusion: DTMF is a reliable technique for very long distance data transmission & Communication. Though Genave SuperFast rate (DTMF Encoders Manual) of 20/20 (25 tones per second) from an automatic encoder or Genave decoder has the ability to send 40 digits per second, means 320 bits per second as each digit or character is a combination of two DTMF tones each tone contains four binary bits. It can be used in further research work to increase the transmission rate for underwater communication. The hydrophone used in this system only can receive acoustic signals in 10-15 meters depth only. If a bit high cost hydrophones are used then this protocol can be used for deep water research purpose. This prototype is very much reliable and affordable for different underwater research works.

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