PAPR reduction using SC-FDMA in Underwater acoustic channel

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Abstract

Underwater acoustic sensor networks (UWASN) have been developing and attracting growing interests recently. However, underwater acoustic (UWA) communications undergo multipath, delay and limited bandwidth. Orthogonal frequency division multiplexing (OFDM) is suitable for UWA communications because of their immunity against frequency selective fading. It can mitigate inter-symbol interference (ISI). But, OFDM is highly sensitive to the frequency offset, and it also has large peak-to-average power ratio (PAPR). This new modified technique of OFDM is called Single carrier frequency division multiple access (SC-FDMA). SC-FDMA has only single carrier, so it has reduced PAPR. Pulse shaping technique using raised cosine filter reduces PAPR. Based on pulse shaping, the Nyquist filter is used to reduce the PAPR. The complexity and design of this technique is simpler. The bandwidth efficiency is not affected. Also, there is less of In Band as well as Out band distortion. SC-FDMA is applied to UWA channels and MATLAB is used for simulation. For both OFDM and SC-FDMA, Bit error rate (BER) and PAPR will be calculated. The result should show that the less bit error rate than the BER of 10^{-3} which is the average can be achieved using SC-FDMA in UWA.

Keywords: SCFDMA, Underwater Acoustic Channel, PAPR, Pulse shaping

INTRODUCTION

UWASN has found an attractive use in a various range of applications, such as military purposes, disaster prevention, remote control in offshore field, pollution monitoring and resource research. There is a need of underwater communications between surface station and underwater sink. Communication between underwater devices is also realized. [1]. The UWA communication channel is complex in nature. The complexity arises due to the inhomogeneous nature of the channel. The various faults are due to salinity, density, temperature changes and inhomogeneity of the water. These are in turn due to the solid or gaseous suspended particles. This are mainly caused by the regular water motion which isn't a problem in aerial. Even the channel perimeter like the bottom and the surface reflects the signal causing multi-path phenomenon which in turn causes ISI and reverberation. The intensity of acoustic wave degrades mainly due to spreading and absorption phenomenon, as it propagates. This is called as transmission loss. Inshore areas got more noise than deep water environment. Ambient Noise affects the Signal to Noise ratio (SNR). Doppler spread is mainly due to the motion of both transmitter and receiver. The range of frequency is decreased. This four aspects are repeatedly varying in nature. The communication system modifies their effects by constantly tracking variations. These factors vary temporarily in the acoustic channel. Thus, making the bandwidth dependent on both distance and frequency. Small bandwidth is present in long range while a short range system have more bandwidth [2].

Underwater environments have low attenuation of sound. OFDM communication has become an attractive modulation technique for UWA communications [3]. The main benefits of OFDM are that it can handle the multi-path interference, and mitigate inter-symbol interference (ISI) caused by the multipath. It divides the available bandwidth into subcarriers and in the process causes bit error rates in frequency selective fading. Channel coding plays a vital role on the performances of OFDM based wireless system. It provides high data rates communication over multipath channels [2]. But, OFDM is erroneously sensitive to the Doppler variation, sampling deviation and have high PAPR.

DFT-precoded version of OFDM is called as SC-FDMA. It has instigated lot of interests in wireless communication because of its reduced PAPR effects. In transmitter side, it uses single carrier modulation and in the receiver side, frequency domain equalization respectively. SC-FDMA signal has single carrier structure. Power efficiency and less implementation cost are the advantages of low PAPR. Another advantage is that data detection is performed in time domain.

PULSE SHAPING BASED SC-FDMA TRANSCEIVER

In SC-FDMA (DFT spreading FDMA), DFT converts the symbols from time domain into frequency domain as understood. Than the modulator converts the input sequence into a complex numbers sequence. This M modulated symbols are grouped into each block. Then, each of the output of DFT will be corresponding to one of the N subcarriers. In SC-FDMA, number of subcarriers N must be greater than symbols M.

The outputs of DFT is allocated to the whole bandwidth and the unallocated subcarriers is occupied by zeros, in the distributed subcarrier mode. The interleaved SC-FDMA (IFDMA) is more preferable than the localized mode because IFDMA is superior in terms power efficiency [8]. Whereas in the IFDMA, to avoid adjacent interference, subcarriers are divided equally over the entire bandwidth. Towards the end, subcarrier is converted back to complex time domain signal by inverse FFT (IFFT) [4].

The ISI has to be removed from IFFT signal. For that case, cyclic prefix (CP) is added in which cyclic convolution is used. A pulse shaping which is also called as linear filtering, is used for PAPR reduction to suppress the out band signal [10]. Then, the modulated subcarriers is convolved with the filters impulse response. Pulse shaping (PS) is needed in order to bandlimit. But, the PAPR is increased in the process [4].
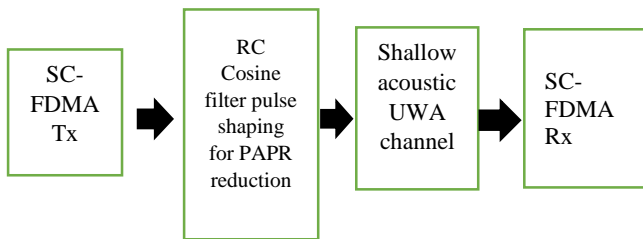

Figure 1: Proposed block model

MULTIPATH UWA CHANNEL

The bandwidth for acoustic is limited which is better supported at low frequencies. Frequency of an acoustic system ranges from 10 kHz to 15 kHz. The bandwidth is 5 kHz which is low, but actually it is in fact ultra-wideband. 1500 m/s is the speed of sound underwater as compared to the aerial. Delay spreading in a long term causes a frequency selective distortion and motion under water causes a Doppler effect. This can lead to reverberation and ISI. UWA channel has the combination of low physical link quality and high latency. Reflection and refractions are the main cause of multipath formation. The multipath formation can be through surface and bottom of the channel [5].

UWA channel has the surface and bottom reflection properties. The geometry of the channel and its reflection properties are the two factors on which the impulse response depends. These determines the number of multiple propagation paths, delays and strengths. Those that have went through multiple reflections are discarded as they lost much of energy. Let us denote the length by l_p of the p-th propagation path, whereby p = 0 corresponds to the propagation path arrived first. In shallow depth, the sound speed is constant c, plain geometry is used to calculate path lengths and path delays is l_p/c. The arrival time of strongest path is value t_0. It calculates the reference time at the destination. Path delays can be given as $\tau_p = l_p/c - t_0$ [5].

Under ideal condition, value of Surface reflection coefficient Γ_p is -1. Bottom reflection coefficients depends on the

smoothness of surface and also the angle between the incident and the horizontal axis i.e. grazing angle. Γ_p is the cumulative reflection coefficient and A_p is the propagation loss associated with that pth path. The gain of this path will be $g_p = \Gamma_p/\sqrt{A_p}$. The channel response usually for a radio channel can be expressed as,

$$g(t) = \Sigma\, g_p \delta(t - \tau_p) \tag{1}$$

The path gain depends on frequency in an acoustic environment. Therefore, only for a single frequency tone, it is constant. Each frequency will undergo an attenuation for a broadband signal. With the attenuation, the p-th path frequency response is,

$$G_p(f) = \Gamma_p /\sqrt{A(l_p, f)} \tag{2}$$

So, the path is a low pass filter, with its own dispersion. In the frequency domain, the overall channel response is

$$G(f) = \Sigma G_p(f) exp(-j2\pi f \tau_p) \tag{3}$$

and the impulse response is

$$g(t) = \Sigma g_p(t - \tau_p) \tag{4}$$

where $g_p(t)$ is the inverse Fourier transform of $G_p(f)$ [5].

MATHEMATICAL MODEL FOR UWA

The acoustic path loss is [6]:

$$A(l, f) = A_o l^k \alpha(f)^l \tag{5}$$

Where k is the spreading factor, l is the distance, A_0 is a unit-normalizing constant and $\alpha(f)$ is the absorption coefficient. Using Thorp's empirical formula, the absorption coefficient can be given as [6]

$$a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75\ x\ 10^{-4}f^2 + 0.003 \tag{6}$$

Where f is given in kHz and the absorption coefficient is given in dB/km. The attenuation and cumulative reflection coefficient are summed together. Therefore, in frequency domain, the overall transfer function can be denoted as follows [5]:

$$G(l, f) = \sum_{p=0}^{P-1} \frac{\Gamma_p}{\sqrt{(A(l_p,f))}} e^{-j2\Pi f \tau_p} \tag{7}$$

Where $\tau_p = l_p / c$ is the path delay and c is the speed of the sound underwater (1500m/s). For paths each of length l_p, $p=0...P-1$, Γ_p shows additional losses on the pth path and is given as follows [6]:

$$\Gamma_p = \gamma_s^{n_{sp}} \gamma_p^{n_{bp}} (\theta_p) \tag{8}$$

Where θ_p is the grazing angle between the received signal and the horizontal axis associated with the pth path, γ_s is the surface reflection coefficient and γ_p is the bottom reflection coefficient. n_{sp} and n_{bp} being the number of surface and bottom reflections. Each bottom reflection is modeled by a coefficient $\gamma_b(\theta)$ [6]:

$$\gamma_b(\theta) = \begin{cases} \dfrac{\rho_b \sin(\theta) - \rho \sqrt{(\frac{c}{c_b})^2 - \cos^2(\theta)}}{\rho_b \sin(\theta) + \rho \sqrt{(\frac{c}{c_b})^2 - \cos^2(\theta)}}, & \cos(\theta) \leq c/c_b \\ 1 & , otherwise \end{cases} \quad (9)$$

Where ρ and c are the density and speed of sound in water respectively. ρ_b and c_b are the density and speed of sound in bottom [6].

The ambient noise is Gaussian distributed because it is random and the distribution are not known. Considering a fixed carrier frequency f and around it a band of frequencies of width Δf, SNR is calculated by:

$$SNR = PD/A.N \quad (10)$$

where PD is the power spectral density, whose power is dependent on the distance, N is ambient noise and A is acoustic path loss [5].

NOISE CONSIDERATION IN UWA CHANNEL

Ambient noise is a kind of a background noise present in UWA channel. Depending on the frequency, ambient noise can be turbulence noise, shipping noise, wind noise and thermal noise [6] described in Table I.

Table I: Ambient Noise

Types	Frequency	Cause
Turbulence noise	0.1Hz – 10Hz	Water motion
Shipping noise	10Hz – 100Hz	Ship traffic
Wind noise	1kHz – 30kHz	Wind and rain
Thermal noise	+100kHz	Water molecules vibration

Since my project deals with frequency 10kHz to 15Hz for a shallow water, wind noise can be considered. Wind noise can be calculated by:

$$10 \log N(f) = 50 + 7.5 \sqrt{w} + 20 \log(f) - 40 \log(f + 0.4) \quad [11]$$

where w is the wind speed in m/s [6].

PAPR REDUCTION USING RAISED COSINE FILTER

The PAPR is the ratio between the maximum power to the average power. PAPR is different at separate instant of phase values. A peak in the output envelope is caused when all the points obtain the maximum value consecutively [9]. The peak value of the system is very high due to numerous modulated subcarriers. It is the fluctuation of peak power or instantaneous power from the mean. Peak can swing and crosses into

nonlinear region, orthogonality is lost. This peaks leads to amplification inefficiency and cost becomes high. It causes saturation in power amplifier. In the process, the complexity of both analog to digital and digital to analog converter is well increased [7].

Peak power is N times greater than the average power. OFDM signals are highly sensitive. That's because of the nonlinearity of the power amplifier. Each symbol is modulated to each of a group of subcarriers, ($k = 0,1,.....,N$ -1). In the process, a block of N symbols (X) is generated. The resulting signal is given as:

$$x(t) = \sum_{n=0}^{N-1} X_k e^{j2\Pi f_k t}, \quad (12)$$

PAPR is defined as,

$$PAPR = \frac{\max|x(t)|^2}{[E|x(t)|^2]} \quad (13)$$

where $E[.]$ denotes the expectation operator.

The PAPR can be handled by both modulation and pulse shaping. The Nyquist pulses have different decay rates. Its decay rate has a huge effect on PAPR. PS filter's two biggest sidelobes causes the PAPR to increase. The reduced size tail of the side lobe of the SC-FDMA can reduce the PAPR [7].

Raised Cosine Pulses are the modified sinc pulses. It has a bandwidth of W where $W = 1/2T_s$. It has an adjustable bandwidth which varies from W to $2W$. The achieved bandwidth is related to the ideal bandwidth as $\alpha = 1 - W/W_o$ where α is the roll-off factor, W is the Nyquist bandwidth and W_o is the utilized bandwidth. The roll off factor value ranges from 0 to 1. The raised cosine pulse in the time domain is [11]:

$$h(t) = \frac{\sin \frac{2\Pi t}{T_s}}{2\Pi t} \frac{\cos 2\Pi \alpha t}{1 - (\frac{2\alpha t}{\Pi})^2} \quad (14)$$

Sinc pulse is the first part. Whereas, the second part is the cosine correction of the sinc pulse. The Nyquist Bandwidth is greater by a factor of $(1 + \alpha)$. Bandwidth depends on the roll-off factor α. For $\alpha = 0$ it becomes a sinc pulse and for $\alpha = 1$, it becomes that of pure square pulse [11]. The frequency domain relationship is given by [11]:

$$H(f) = \left\{ \cos^2 \frac{\Pi T_s}{2\alpha} \left[|f| - \frac{(1-\alpha)}{2T_s} \right] \right\} \begin{array}{l} for |f| \leq \frac{1-\alpha}{2T_s} \\ for \frac{1-\alpha}{2T_s} \leq |f| \leq \\ for |f| > \frac{1+\alpha}{2T_s} \end{array} \quad (15)$$

SIMULATION RESULTS AND DISCUSSION

Simulations in MATLAB was done to study the PAPR performance and SNR characteristics considering ambient noise and path loss. Pulse shaping used to obtain better PAPR performance.

Table II: Simulation Parameters

Bandwidth	5kHz
Frequency	10kHz
Transmission distance	3km, 5km and 10km
Size of the block N_d	480
No. of subcarriers N	2400
Subcarrier spacing	2.3Hz
Duration of data block T	434ms
CP duration T_{cp}	16.8ms
Spreading factor k	1.5
Roll off factor	0, 0.5, 1
Surface reflection coefficient Γ_s	-1
Number of surface and bottom reflection	1

The CCDF is the probability that the calculated PAPR of the output signal exceeds a threshold value. So, it is 1-CDF. As, rolling factor increases, PAPR reduces and reduced tail size. Further the curve towards the right, it has high PAPR.

10% probability that PAPR is greater than 6.3dB for SC-FDMA (rolling factor 1) compared to rolling factor 0.5 whose 10% probability that PAPR is greater than 7.1dB. There is more deviation for rolling factor for rolling factor 0.5 than rolling factor 1 from 0dB. So, comparatively with rolling factor 1 has better PAPR reduction than OFDM. The maximum reduction in PAPR value of about 8 dB is achieved by SC-FDMA.

Figure 2: PAPR of UWA SCFDMA system
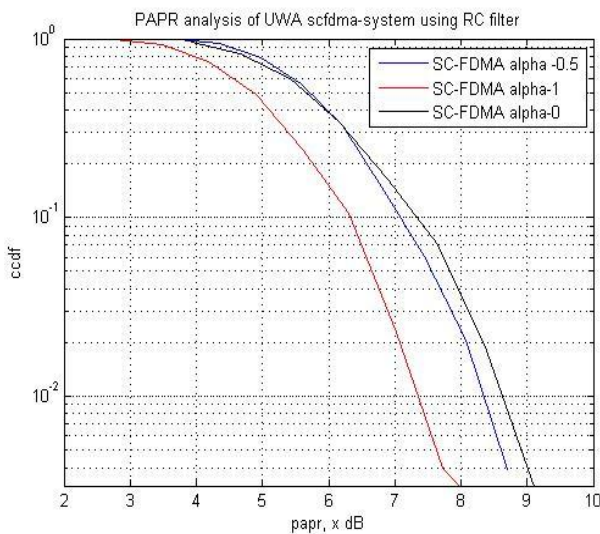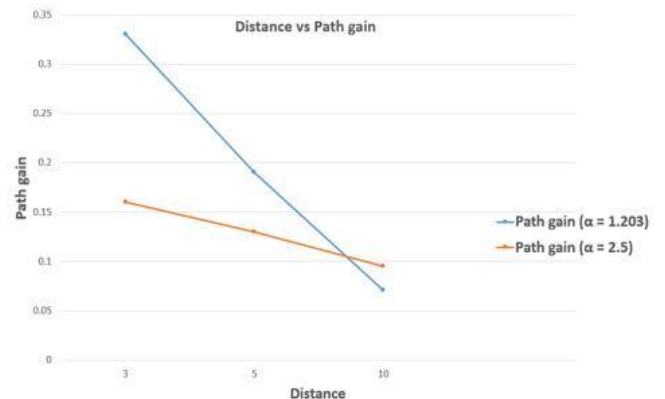
Table III: 3 Multipath UWA Channel Analysis for Frequency 10khz.

Transmission length l (km)	Path delay τ (s)	Path loss A (dB)	Absorption coefficient	Path gain (Γp/√A)
3	2	19.1		0.33
5	3.33	28.99	1.203 dB/km	0.19
10	6.66	46.1		0.071

Table IV: 3 Multipath UWA Channel Analysis for Frequency 15khz.

Transmission length l (km)	Path delay τ (s)	Path loss A (dB)	Absorption coefficient	Path gain (Γp/√A)
3	2	38.19		0.16
5	3.33	60.76	2.5 dB/km	0.13
10	6.66	109.59		0.095

In Table II, path gain and path loss was analyzed for frequency 10 kHz for 3km, 5km and 10km respectively. The absorption coefficient is 1.203 dB/km calculated from equation (6). We know that in a UWA channel as transmission length increases, path gain decreases. Similarly in Table III, it was calculated and studied for frequency 15 kHz with the increased absorption coefficient 2.5dB/km.


Figure 3: Distance vs Path gain for different absorption coefficient

In figure 3, I have plotted the graph between distance and path gain for absorption coefficient 1.2 and 2.5. When absorption coefficient increases path gain decreases but for 10km distance, the path gain increases. For absorption coefficient 1.203, path

gain decreases drastically but for 2.5, its not a drastic decrease rather it's a slow decrease.

From figure 4, we can conclude that BER remains constant for increase of SNR till 5dB. Than after that it starts decreasing.
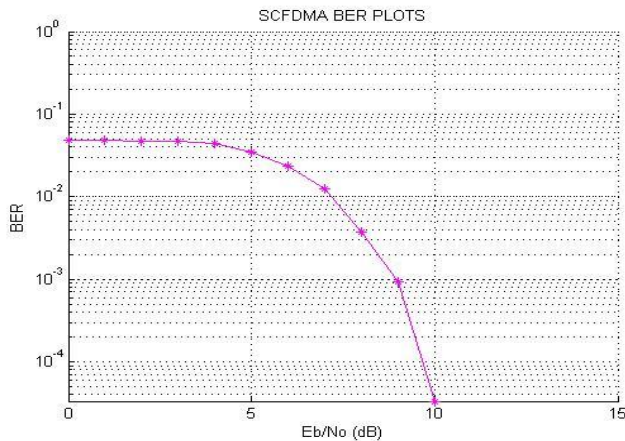
Figure 4: BER vs SNR for SC-FDMA UWA

CONCLUSION

UWA is a complicated channel due to its bandlimited and reverberant nature. SC-FDMA can be an appropriate solution for UWA channel which takes the advantage of OFDM to handle multipath and also the reduction of PAPR. To reduce the PAPR of the system, pulse shaping is used. The complexity and design of the technique is simpler as only a simple RC filter is used. There is very low in band as well as low out band distortion. This technique doesn't affect the bandwidth efficiency of the system.

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