

Performance Evaluation of a MIMO based Underwater Communication System under Fading Conditions

Boddu Pranitha

Department of Electronics and Communication Engineering
National Institute of Technology
Warangal, Telangana, India
pranitha.boddu@nitw.ac.in

L. Anjaneyulu

Department of Electronics and Communication Engineering
National Institute of Technology
Warangal, Telangana, India
anjan@nitw.ac.in

Abstract—Due to the intense importance of underwater applications in military and commercial purposes, Underwater Acoustic Communication (UWAC) is an attracting research area. Very high propagation delay, path loss, and low bandwidth are the factors that challenged the acoustic waves in an underwater environment. Multi-Input Multi-Output (MIMO) techniques are currently considered in UWAC to surpass the bandwidth limitation of the undersea channel. In this paper, the accomplishment of a MIMO in UWAC System highlighting both Line of Sight (LOS), i.e. the Rician fading and Non-Line of Sight (NLOS), i.e. the Rayleigh fading signal propagation, is assessed. Spatial Modulation technique is used, which helps in increasing the data rate in UWAC. It controls the spatial distribution of the energy caused by a signal in such a way that the single ocean channel sustains multiple parallel communication channels. The utilization of Zero Forcing (ZF) equalizer, which estimates the transmitted data proves the success of removing Inter Symbol Interference (ISI). Matlab simulations are done for the UWAC system for values of LOS/NLOS. Because of various scattering effects in NLOS propagation, the error rate is considerably high when compared to that of the LOS propagation. Bit Error Rate (BER) values for the corresponding Signal to Noise Ratio (SNR) are calculated.

Keywords—Underwater Acoustic Communications (UWAC); Multiple Input Multiple Outputs (MIMO); Rayleigh fading; Non-Line of Sight (N-LOS); Rician fading; Line of Sight (LOS)

I. INTRODUCTION

Nowadays, Underwater Acoustic Communications (UWAC) is an open research, which includes the present day expansion of human activities in undersea environments, i.e. environmental monitoring and offshore oil field exploration. Robotics in underwater environment is also becoming a major aspect of research in UWAC in order to increase precision [1]. Today, underwater remote sensing systems such as SONARs are used extensively for detecting and tracking different targets using sound signals [2]. Recently, significant attention has been given to the Underwater Wireless Sensor Networks (UWSNs) because of their applications in commercial, scientific, environmental and military purposes [3-4]. The performance and reliability of the system have been improved due to the

continuing research. Because of underwater high attenuation and absorption effect, electromagnetic waves can travel only short distances [5]. Some investigations have been made about utilizing optical signals for underwater applications. However, it was found that they can only pass through a limited range in a very clean water environment, making them useless for underwater long-distance transmissions [6]. Thus, acoustic signals are found to be the only physical feasible way that works in an underwater environment reducing bandwidth limitations [7]. High propagation delay, heavy energy consumption, large path loss, and low bandwidth have posed challenges for applying acoustic waves in underwater environment [8]. Three major factors that characterize acoustic wave propagation are attenuation, multipath propagation that varies along with time, and low sound speed. Attenuation increases with the frequency of the signal [9]. Fading, usually called small scale fading, is caused by multipath signals. The signal may be constructive or destructive [10]. Generally, these factors limit system performance. Three factors that characterize the channel in UWAC are long multipath delay, high Doppler spread, and time-varying Doppler shift. This multipath delay is the main cause of Inter-Symbol Interference (ISI). Doppler spread, and Doppler shift are caused due to relative speed that is comparable with the speed of sound [11]. Severely low bandwidth, large area multi-path spread, Doppler shift, and background noise make the underwater environment much more complicated than a simple wireless channel. Hence, the design and implementation of high data rate UWAC are a major challenge.

Influence of interference in Wireless Communication has been studied in fading environment using outage probability calculation [12]. In low frequency (i.e.<1kHz) sound propagation, the fading components, Rayleigh and Rician are related with saturated and partially saturated schemes respectively in which the multipath is completely or partially random. The propagation of acoustic waves requires a medium to transmit data. This medium can be either shallow or deep water. Irrespective of the type of the medium, propagation loss and fading exists. Propagation loss, also known as path loss is the value of the power of the receiver at the receiving end.

Corresponding author: B.Pranitha

Distance in the propagation (considering LOS and NLOS), water density, strong currents, waves, etc. are factors that impact path loss. Because of the presence of living and non-living objects underwater, a portion of the acoustic signal gets either reflected or diffracted and scattered. This is referred to as slow fading in UWAC, while fast fading is caused due to multipath propagation loss. Considering all these issues, the main focus of our research is to characterize all the mentioned properties in the UWAC channel. Estimating the transmitted signal in UWAC is to be studied as well [13].

Multiple Input Multiple Output (MIMO) is the advanced and sophisticated technology which is adapted from land wireless communication to underwater communication because of the increasing demand for high data rates. In this paper, this technique is used which helps in reducing the interference of UWAC systems. Also, spectral efficiency in multiple transmitters can be increased [14]. MIMO techniques are applied to UWAC with spatial modulations [15]. MIMO approaches have taken advantage of available channel equalization algorithms that are used for single carrier transmissions [16]. The bandwidth of the transmitting and receiving means of MIMO occupy the same frequency band, without the use of any further receiver transmitting power. This can increase the capacity of the channel and lessen the Bit Error Rate (BER) of the system [17]. Whenever the transfer functions between different transmitting and receiving antennas are identically and independently distributed (i.i.d.) and their significances are explained by the Rayleigh distribution, then an ideal situation arises for a MIMO system. This distribution describes the conditions for NLOS signal propagation. However, it can be noted that UWAC scenarios deviate from the given ideal conditions as they give signal propagation details of LOS and NLOS which are expressed as Rician distribution and Rayleigh distribution respectively. To recover the data that is transmitted, Zero Forcing (ZF) equalization technique is used. An equalizer is a digital filter used to mitigate the effects of ISI introduced by a time dispersive channel. MIMO linear equalizer is used to attain low-complexity equalization. It reduces the error propagation. ZF equalizer is a linear equalization algorithm used in communications. It generally affixes the inverse of the frequency response of the channel matrix. This technique is used when ISI is high compared to the noise in the system. This technique is generally ideal in the case of noiseless channels. A ZF equalizer controls the ISI and ICI introduced by the transmission channel. This equalizer does not take enhancement of the noise into consideration [18].

In our previous work [19], a comparison for ZF equalizer and LMS equalization has been made in UWAC for a 2×2 MIMO in which ZF equalization outperforms LMS equalization technique. In this paper, the ZF equalization technique at the receiver will be compared for Rayleigh and Rician fading UWAC MIMO channels. Rician fading includes the LOS while the Rayleigh fading has the N-LOS component considering multipath of UWAC in it. All the losses included in UWAC channels such as spherical loss and absorption loss were considered. The Doppler effect and the relative motion that exists between the transmitter and receiver were also considered. LOS and N-LOS links consider that the wave

reflections are not significant, i.e. the transmitter and receiver are neither near to water surface nor to the seabed. Matlab simulations have been carried out for all these conditions, and the results were compared.

II. SYSTEM MODELING

To reduce bandwidth limitation to the most extent of the undersea channel, MIMO is considered in UWAC. Multiple antennas are used by MIMO technology to acquire various gains namely multiplexing and beam forming. Nonetheless, the complexity and cost of the receiver are increased because of these gains. Spatial Modulation (SM) is one good approach to overcome the problems mentioned above. In SM, the information bits are mapped into two different constellations: a signal constellation and a spatial constellation. Signal constellation is based on the modulation scheme, while the spatial constellation is used to encode the index of the transmitter. At any point in time, one of the transmitters remains active, while the other transmitter radiates zero power. Thus, SM avoids the Inter Channel Interference (ICI) at the receiver and reduces the high requirement of synchronization among transmitters. Moreover, unlike the regular MIMO system, RF chains are not required in SM at the transmitter [20]. In this part, we start by giving an introduction to SM-MIMO concept in UWAC. This modulation scheme is applied to the transmitting or receiving antenna to send extra information, and so SM is used to find the index of the active antennas at any time instance. Therefore, the information bits that are to be transmitted are branched into two different parts. In the first part, they are graphed to a symbol from the signaling constellation. Here the type of modulation used finds the number of bits per symbol. From the set of receivers available for transmission or reception, the second part of the information bits regulate the index of the receiver that is selected from a set of receivers that are available for transmitting or receiving the data. Receiver selection in any general MIMO system depends on the state of the channel and the signal strength of the receiver. In SM-MIMO it depends on the incoming user data stream [21].

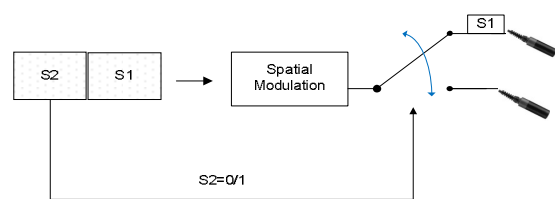


Fig. 1. Spatial modulation

The number of transmitters and receivers is N_t and N_r , respectively. M is the number of entities of the signal constellation. Here we are considering a 4-QAM modulation because of its bandwidth efficient quality. By finding the index of the active transmitter in SM-MIMO, one symbol S_1 is transmitted directly, and the other symbol S_2 indirectly in each channel use. For subjective N_t and M , the rate of SM is:

$$R_{SM} = \log_2 M + \log_2 N_t \quad (1)$$

Hydrophones are used as transmitters as shown in Figure 1. Higher throughput, simpler receiver and transmitter design, and lower transmit power supply are the main advantages of SM-MIMO. But the antenna has to be switched very quickly in this case. Here, a basic 4 QAM modulation is used. The received data for the 2×2 MIMO is given by:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad (2)$$

where y_1, y_2 are the received data from the two receivers, $h_{11}, h_{12}, h_{21},$ and h_{22} are the channel coefficients explained below, x_1 and x_2 are the transmitted data and $n_1,$ and n_2 represent the UWAC noise. To detect the data at the receiver, a ZF equalizer is used. Detecting the information from the original noisy data being received is known as detection. MIMO detectors/receivers include a merge of many algorithms carrying out many tasks like estimation, detection, equalization, decoding, etc. [22]. In this paper, the ZF equalizer, which is based on channel matrix estimation, is put forward. The original system is divided into several subsystems allowing data estimation with practicable complexity. The inverse of the channel matrix is calculated and multiplied with the received data to obtain the transmitted data. The estimated/detected data is given by:

$$\hat{x} = H^{-1}Y \quad (3)$$

$$\hat{x} = H^{-1}(Hx + n) \quad (4)$$

$$\hat{x} = x + H^{-1}n \quad (5)$$

ZF technique is less complex. The number of receivers should be equal to or greater than the number of transmit antennas in the case of ZF. However, it comes at the cost of increasing the power of noise that leads to power degradation [23]. When the Doppler frequency is small, the received signal quality will be better than when it is large. Consequently, it will influence the received signal quality. Interference between terminals can be suppressed further by using the ZF equalizer.

III. CHANNEL MODELING

The UWAC channel is highly complex because of its non-homogenous nature. Water densities, temperature gradients, and non-homogeneities caused by the dropping particles of either solid or gaseous matter are the main reasons for most imperfections. The constant flow of water and the channel reflections that are caused at the sea surface and bottom increase the complexity further. This effect of the underwater channel is that it has strong multi-path propagation and the Doppler spread. However, salinity, temperature, and pressure help in finding the propagation velocity, which makes the transmission medium highly refractive [24]. The received signal combines a large number of multipath arrivals, especially scatterers formed by ocean surface and bottom. Such fading is known as a Rayleigh fading channel. Rayleigh fading channel is a shallow water channel commonly used, but when discrete arrivals are seen in the channel response, it imposes a challenge to make assumptions [25]. Point-to-point communications in UWAC are a major research area that has to be studied. This is known as LOS communications to underwater multicarrier modulation networks. Because of the

presence of multipath scattering in the UWAC channel, the application of MIMO is promising in this case. Large fractional bandwidth is one of the main difficulties associated with UWAC. The acoustic multipath propagation in Rayleigh fading model follows an exponential distribution at the received power, while in a LOS propagation path, the Rician fading model is adapted [12]. When the Rayleigh fading model is used, the scatterers that are explained in Figure 2 are considered.

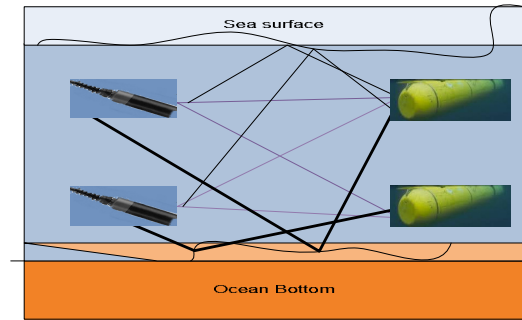


Fig. 2. Multipath scattering in UWAC

In this type of channel, no straight path exists between the transmitter and the receiver, but at the receiver, the sums of all the reflected and scattered waves are combined. Scattering may be mainly caused due to reflections from the sea surface and the ocean bottom. At the receiver signals are received in four different ways. They are the direct LOS direction between the transmitter and the receiver, the reflected signal from the bottom of the ocean surface, and the reflected signal from both surface and bottom. However, each receiver receives multiple reflected and direct signals from each transmitter. Figure 2 depicts the scattering scenario in UWAC. Rough sea surface or the seafloor causes attenuation of the acoustic field in an ocean waveguide. Here, attenuation increases with increasing frequency. Ambient noise is considered in the Rayleigh fading UWAC channel due to turbulence, shipping, ocean waves, and thermal noise [26]. The power spectral density (PSD) of these noise components as a function of frequency in kHz is expressed as:

$$\log N_t(f) = 1.7 - 3 \log f \quad (6)$$

$$\log N_s(f) = 4 + 2 \left(s - \frac{1}{2} \right) + 2.6 \log f - 6 \log(f + 0.03) \quad (7)$$

$$\log N_w(f) = 5 + 0.75w^{1/2} + 2 \log f - 4 \log(f + 0.4) \quad (8)$$

$$\log N_{th}(f) = -1.5 + 2 \log f \quad (9)$$

The shipping coefficient s varies from 0 to 1, for low and high action respectively. w is the wind speed (m/s) [27]. The final PSD of the background noise is given by:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (10)$$

where $N_t(f)$ is the noise due to turbulence, $N_s(f)$ the noise due to the shipping activity, $N_w(f)$ is caused due to waves and $N_{th}(f)$ is the thermal noise.

In a Rician fading channel, the LOS component is mainly due to ocean currents, pressure and temperature gradients, and

salinity variations. The channel coefficients of UWAC in LOS are calculated as:

$$h = \sqrt{\frac{c_R}{1+c_R}} A_s(d)A_a(d)e^{j(2\pi f_0 t + \theta_0)} \quad (11)$$

where c_R is the rician factor, $A_s(d)$ is the propagation loss coefficient due to spherical spreading, and $A_a(d)$ is the absorption loss. f_0 gives the Doppler frequency and θ_0 represents the phase shift of this LOS component [28]. While evaluating the channel coefficients, all the factors involved in effecting the performance of the system are considered. Due to the motion between the source, the receiver and the inhomogeneous ocean medium, sound waves are affected by Doppler shift which results in frequency spread in the received signal [29]. The Doppler frequency f_0 is expressed as:

$$f_0 = f_{max} \cos(\alpha_0 - \alpha_v^R) \quad (12)$$

where f_{max} is the maximum Doppler frequency given by:

$$f_{max} = v_R f_c / c_s \quad (13)$$

where v_R is the receiver's speed, f_c gives the carrier frequency, and c_s denotes the sounds speed, which is generally considered as 1500m/s. The factors α_0 and α_v^R are considered when there is an angle of arrival between the transmitter and the receiver. Different water properties such as temperature, salinity and pressure impact the speed of sound in water. The speed of sound in water near the surface is approximately 4 times faster than the speed in the air.

The propagating signal phase shift can be calculated as:

$$\theta_{ij} = \frac{d_{ij}}{2\pi} * \lambda \quad (14)$$

where i is the i^{th} transmitter and j is the j^{th} receiver. The wavelength λ is given by

$$\lambda = 1500/f_c \quad (15)$$

If the signal gets weakened because of the geometrical spreading of a wave propagating away from the source, then the created loss is known as spreading loss. Different kinds of non-uniformities are present in the sea and within its boundaries. These inhomogeneities reradiate a portion of the acoustic energy that is incident upon them which is known as scattering. Due to the presence of geometrical spreading and absorption spreading, as an acoustic wave propagates through the medium, its intensity is reduced. However, there is a drastic change in the attenuation of acoustic waves in water when compared to the RF waves in water. Also there is a heavy loss of energy in water due to absorption. The loss that is caused by geometrical spreading can be either spherical or cylindrical. The loss due to spherical spreading is calculated by:

$$A_s(d) = \frac{1}{d} \quad (16)$$

where d is the distance between the transmitter and the receiver.

During sound wave propagation, energy can be converted to many other modes, and the medium absorbs it. The propagating physical wave controls the absorptive energy loss.

The absorption loss according to the Schulkin-Marsh model is calculated as:

$$A_a(d) = 10^{\frac{-d\beta}{20000}} \quad (17)$$

The parameter β is given by:

$$\beta = 8.68 * 10^3 \left(\frac{S_a f_T f_c^2 A}{f_T^2 + f_c^2} + \frac{B f_c^2}{f_T} \right) * (1 - 6.54 * 10^{-4} P) \quad (18)$$

where A and B are constants, S_a stands for salinity, f_c for carrier frequency and f_T is the relaxation frequency which is given by:

$$f_T = 21.9 * 10^6 - \left(\frac{1520}{T+273} \right) \quad (19)$$

Here T is the hydrostatic temperature given in °C, P denotes the hydrostatic pressure which depends on water depth h_t , which is given by:

$$P = 1.01(1 + 0.1h_t) \quad (20)$$

In Figure 3, two transmitters are placed apart at a distance L_1 , while d_{11} is the distance between the transmitter and the receiver, and L_2 is the distance between the two receivers. It is assumed that the transmitters and receivers are in parallel planes and $L_1 > L_2$. For calculating the channel coefficients $\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$ using (2), we consider distances d_{11} , d_{12} , d_{21} , and d_{22} respectively. Assuming that the distances d_{11} , L_1 and L_2 are fixed, the remaining distances could be calculated. The signal phase shift θ_{ij} can also be determined for various distances.

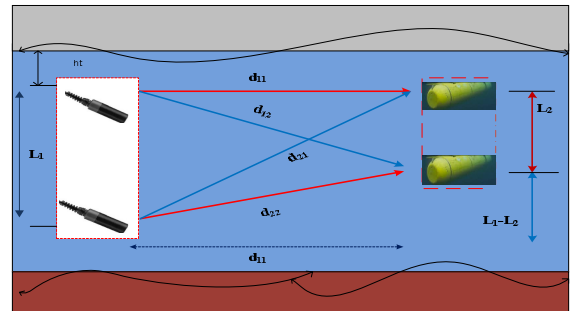


Fig. 3. MIMO LOS UWAC channel

IV. SIMULATION RESULTS

Simulations in Matlab have been carried out for the channel model shown in Figure 3. 4-QAM spatial modulation is given at the transmitter which is a cost and complexity efficient, while at the receiver ZF equalization is utilized to detect the transmitted data. For NLOS, i.e. the Rayleigh fading considers the multipath fading involved in UWAC. The ambient noise which involves noise caused due to shipping, waves, turbulence, and thermal noise is also considered. While in LOS, Rician fading factors such as absorption loss, spherical loss, temperature, pressure, salinity, Doppler frequency, etc. are considered as shown in Table I. Simulations were carried out for both LOS and N-LOS UWAC, i.e. for both Rician and Rayleigh fading channels. Figure 4 depicts that Rician fading outperforms the Rayleigh fading channel. The SNR to BER values are tabulated in Table II.

TABLE I. SIMULATION PARAMETERS

Symbol	Parameter	Value
N_t	Number of transmitters	2
N_r	Number of receivers	2
N	Number of transmitted bits	10000
m	QAM order	4
c_R	Rice factor	0.56
d_{11}	Distance	1m – 100 m
f_c	Carrier frequency	10kHz
T	Temperature	10°C
Sa	Salinity	35 PSU
P	Pressure	11 kg/cm ²
c_s	Speed of sound	1500 m/s
L_1	Distance between transmitters	5 m
L_2	Distance between receivers	2 m
v_R	Speed of the receiver	9 m/s
h_t	Shallow water depth	90m

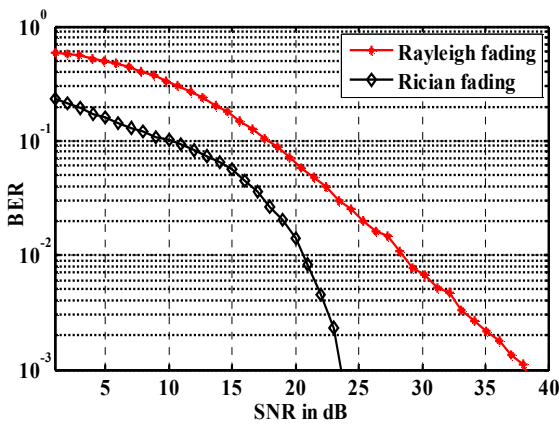


Fig. 4. SNR vs. BER of Rayleigh and Rician fading UWAC

TABLE II. BER VALUES

SNR in dB	BER	
	Rician Distribution	Rayleigh distribution
1	0.830409	0.94646
5	0.782244	0.915555
10	0.731129	0.870501
15	0.658818	0.789072
20	0.474383	0.689473
25	0.020281	0.571698
30	0.00	0.447859
35	0.00	0.324006
39	0.00	0.191

From the above-tabulated values, we can observe that the error rate for Rayleigh distribution is very high when compared to Rician distribution. This is because the scattering effects are very less in the LOS component than in the N-LOS and also the presence of multipath fading affects the performance of the system. From Table II, we notice that the BER values of Rician distribution are zero for SNR values at 30dB. However, the BER value of Rayleigh distribution is 0.448 for SNR at 30dB. For Rician distribution, the distance between the transmitters and the receivers can be varied because of the line of sight propagation. As they are in parallel planes, the channel coefficients can be calculated, and the respective received data can be detected by using the ZF equalizer. From Figure 5 we observe that the error rate increases as the distance from the

transmitter to the receiver increases. As the link distance d_{11} increased from 1m to 100m, it is observed that the geometry of the channel model is varying, thereby introducing larger spherical and absorption losses, calculated by (16) and (17) respectively. Note that as the distance d_{11} varies, all other link distances, which are used to calculate various channel coefficients (h_{11} , h_{12} , h_{21} , and h_{22}) also vary. The phase shifts of the signals propagating in longer paths are recalculated by (14). It is observed that the BER is proportional to the considered distance.

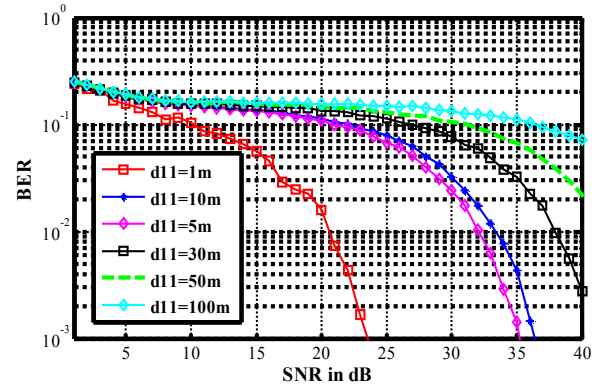


Fig. 5. SNR vs. BER of ZF equalization with different distances

The main intention of using the 4-QAM modulation scheme is its efficiency to use the bandwidth. Generally, whenever the requirement of linearity of a modulation scheme like QAM increases, the power efficiency of the current power amplifiers considerably reduces. So a simple 4-QAM modulation is used in this case of transmission. In Figure 6 we observe that the 4-QAM is the best utilized modulation scheme. Though the higher modulation orders give higher data rates, they are very resilient to noise and interference. Therefore, there is a small deterioration in the performance of 4-QAM between 15 to 23dB of SNR. As SNR decreases, errors will increase along with data retransmitting, thereby slowing throughput. By reverting to a lower order modulation scheme the link can be made more reliable with fewer data errors and retransmissions. So, the 4-QAM is used for better efficiency and reduced complexity.

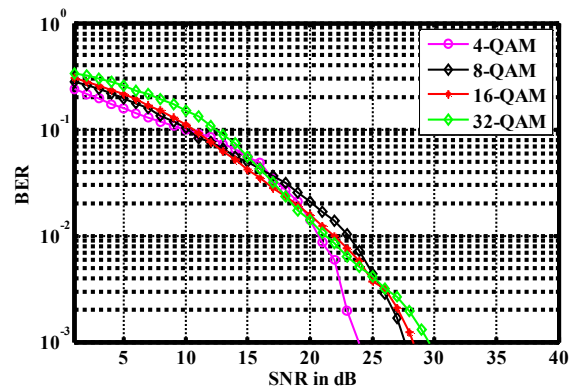


Fig. 6. SNR vs. BER for different states of QAM

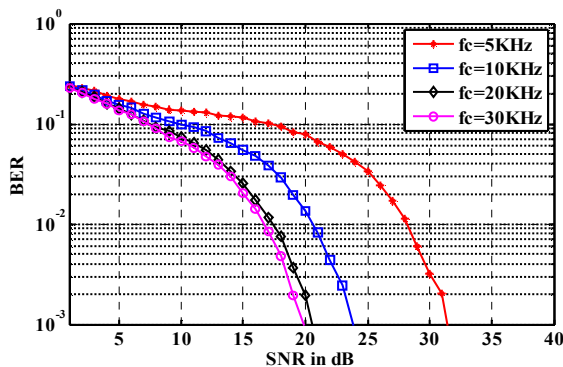


Fig. 7. SNR vs. BER for different carrier frequencies

Figure 7 gives the SNR to BER curve for various carrier frequencies. We observe that the number of errors keeps on decreasing as the carrier frequency value increases. Carrier frequency and the relative motion between the transmitter and the receiver depend upon the Doppler effect. By optimizing the choice of these basis functions, the Doppler shift is estimated. Doppler effect plays an important role in the efficient design of high data rate acoustic communication systems.

V. CONCLUSIONS AND FUTURE WORK

Simulation results prove that the LOS component of UWAC outperforms the NLOS component. All the scattering effects of the undersea channel characteristics are considered in this work. Moreover, in LOS propagation, the performance on varying distances is calculated. Results have been presented for various states of the QAM modulation scheme and also for different carrier frequencies. The shallow water acoustic channel is highly time-varying and does not assuredly follow a Rayleigh distribution. High data rates, high performance and optimum utilization of the bandwidth are the ultimate goals of the future generation UWAC. Many other equalization techniques, which further improve the performance of the underwater system, have to be implemented in this realistic channel, which considers absorption and spherical coefficients. In the future, we aim to develop robust long-range communication in the deep sea with higher data rates based on the proposed modem hardware. Real-time detection of undersea environments has to be studied further. Also, MIMO systems that handle more than two transmitters are to be investigated.

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