Asian Journal of Convergence in Technology **Volume 4 Issue II**
ISSN No.:2350-1146, I.F-5.11

High Data Rate Acoustic Massive MIMO for Underwater Communication

First A. Shaiq Iqbal Arif, *Member, IEEE*
Birla Institute of Technology, Mesra, Patna Campus

***Abstract*—The demand for high definition real time applications for explorations and surveillance of underwater and marine environments is unprecedented, and also in defense applications and autonomous underwater vehicles (AUVs). These applications require high data rate with improved throughput and low error performance in underwater acoustic communications. In this paper, MassiveMulti input multi output (MIMO)technique is proposed with Signal-to-leakage plus noise ratio maximization (SLNR-Max) based precoding method to amplify and achieve the desired performance enhancement. Here, it has been established that by increasing the number of transducers/hydrophones at the buoy station (BS), there is significant improvement in error performance and capacity. Proposed method for underwater communication channel can yield greater performance with high spectral efficiency and low error probability.**

Keywords*—*Massive MIMO; Pre-Coding;SLNR-Max;Underwater Acoustic Communication

II. INTRODUCTION

Recently, there has been an intriguing interest in monitoring underwater environments for scientific and commercial exploitation, and defense preparedness. The devices used consists of autonomous underwater vehicles (AUVs), cabled seafloors, moored sea floors buoy station, etc. as shown in Fig 1. Underwater multimedia monitoring applications require higher demand of data traffic [1]-[2].These requirements include bandwidth and end-to-end transmission reliability. Researchers started to investigate the use of massivemulti input multi output (MIMO) systems for underwater communication due to the promise to address the drawbacks of current technologies and achieve greater bandwidth for transmission. But, underwater communication suffers with low available bandwidth, greatly varied multipath, and high propagational delays, restricting the efficiency of network. The underwater environment or channel is affected by high propagation delay, which may vary based on the direction of propagation of the link (horizontal or vertical), multipath, fading, propagation loss, channel impairment, range dependent spectrum and increasedbit-error-rate (BER)[3]. Proposed massive MIMO for underwater communicationwith Signal-to-leakage plus noise ratio maximization (SLNR-Max) pre-coding to boost the data rate to enable real-time, high quality underwater transmission from an underwater device to a surficial buoy station (BS) with large array of hydrophones [4]. Currently, underwater devices and buoy stations are equipped with less number of electro-acoustic transducers, which degrades the performance to a large extent, and typically forming a single input single output (SISO) system. In massive MIMO system, the buoy station is employed with large number of electroacoustic transducers (large array of hydrophones) to simultaneously communicate with multiple acoustic devices (anchored, floating, etc.) with number of transducers in same time-frequency range, shown in Figure 2.

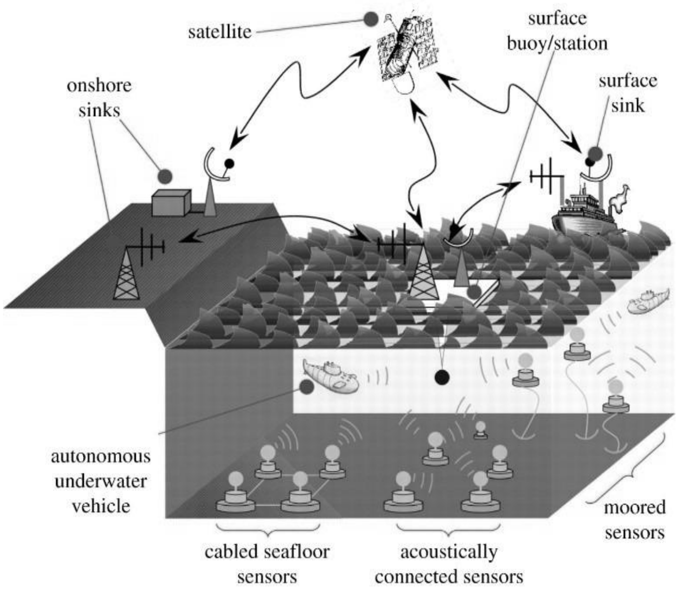

Figure 1: Underwater Acoustic Networks and Devices [11]

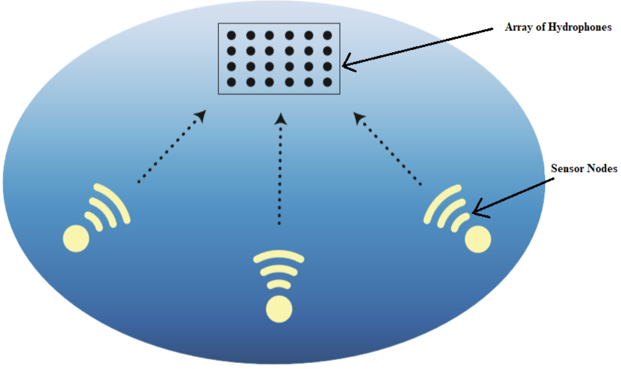

Figure 2: Large Array of hydrophones at a buoy station [5]

II. SYSTEM MODEL

In this section, the channel and buoy station model is shown in Fig 3. QPSK modulation is used at both transmitter and receiver side. Full CSI is used to implement pre-coding. Generalized Eigen value decomposition of two Hermitian matrices has been used to obtain our pre-coding transmitter block.

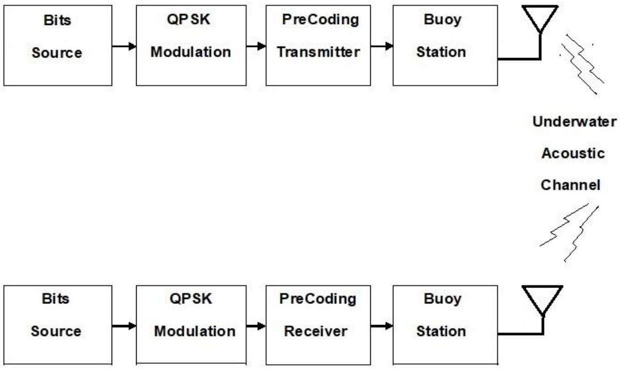

Figure 3: Block Diagram of System Model

A. *CHANNEL MODEL*

When transmitter transmit the signal, due to fading direct line of sight transmission becomes practically impossible and signals reach transmitter in multipath. Rayleigh propagation model is a statistical model which studies the behavior of different multipath propagation signals when there is no direct line of sight (LOS) path possible.

Rayleigh fading channel is useful where a transmitted signal transmits in a form of multipath and no single path is dominant. Due to environmental conditions, signal scatters between transmitter and receiver and no single path remains dominant and reception of every path becomes necessary.

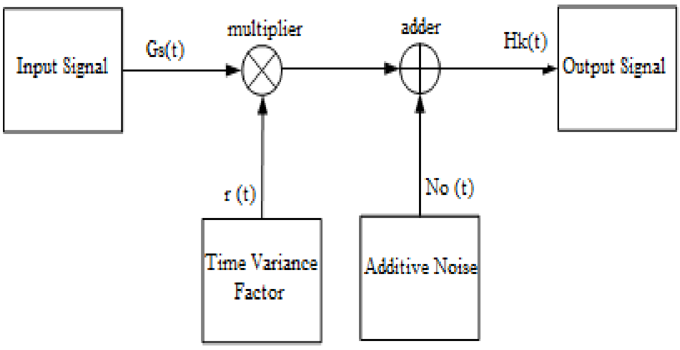

Figure 4: Rayleigh fading channel model for underwater acoustic channel

Here we can write that [9],

$$\boldsymbol{H_k}(\mathrm{t}) = \boldsymbol{G}s(\mathrm{t})\,.\,\boldsymbol{r}(\mathrm{t}) + \boldsymbol{N}o(\mathrm{t})(1)$$

For a particular application, change in parameters changes system. Hence, there is no fixed method available for Rayleigh fading channel technique but it has been widely been in use to study multi path propagation in both air and underwater.

A constant amplitude transmission signal can be given as [10]:

$$\boldsymbol{G}_s(t) = Re(A.e^{j2\pi f_c t})(2)$$

So, received scattered multipath signal is,

$$\boldsymbol{H}_k(t) = R(t).\cos(2\pi f_c t - \varphi(t)) \qquad (3)$$

And,

$$X(t) = \sum a(t).\sin(2\pi f_c t) \qquad (4)$$

$$Y(t) = \sum a(t).\sin(2\pi f_c t) \qquad (5)$$

Where,

$$R(t) = \sqrt{X^2 + Y^2}, \varphi(t) = \arctan(\tfrac{Y}{X})(6)$$

In this a(t) and τ are the amplitude and delay associated with each scattered path.

The envelope R(t) has Rayleigh distribution and $\varphi(t)$ has uniform distribution. Rayleigh channel is used to investigate the properties and applications of underwater acoustic communication channel.

B. *UPLINK TRANSMISSION*

We consider uplink training and transmit precoding which consists of a buoy station with N hydrophones/transducers and K users with single hydrophone/transducer.Let $\mathbf{H}_\mathrm{k} \in \mathbb{C}^{M*N}$depicts the channel from the buoy station to the user$k$ and $\overline{\boldsymbol{H_k}} = [\,H_1^H, \dots, H_{k-1}^H, H_{k+1}^H, \dots, H_K^H]^H \in C^{(K-1)M*N}$represents the consequent leakage channel. A flat Rayleigh channel in high scattering environment is taken. The elements of$\boldsymbol{H}_k$are modeled as free and similar distributed complex Gaussian variables with variance and mean, unity and zero, respectively. Also, we assume,$\boldsymbol{H}_k$and also, $\overline{\boldsymbol{H_k}}$have complete rank with probability unity. For a specific vector time, the transmitted vector symbol of user k is denoted as$S_k \in \mathbb{C}^{L\times 1}$,where$L$ ($\leq M$) is the number of data streams supported for user k and is assumed equal for all the users for simplicity. The Vector satisfies the Gamma (γ), $E(s_k s_k^H) = \boldsymbol{I_L}$.

Before being transmitted, the S$_k$is multiplied by a precoding matrix$\boldsymbol{F_k} \in \mathbb{C}^{N\times L}$. Now for *k* users, the received signal can be

$$\boldsymbol{r}_k = \boldsymbol{H}_k\boldsymbol{F_k}s_k + \boldsymbol{H}_k\sum_{i=1,i\neq k}^{K} F_i s_i + \boldsymbol{n}_k \quad (7)$$

In above expression, there is inter-user interference and AWGN, respectively [6]. SLNR is defined as the ratio of power of signal that reaches to desired user to power of signal that reaches other terminals (the leakage) plus noise power without taking receiving matrix that is given by

$$\mathbf{SLNR}_k = \frac{\mathrm{T}_r(\mathbf{F}_k^H\mathbf{H}_k^H\mathbf{H}_\mathrm{k}\mathbf{F_k})}{\mathrm{T}_r(\mathbf{F}_k^H(M/L\sigma^2\mathbf{I}+\bar{\mathbf{H}}_k^H\overline{\boldsymbol{H}_k})\mathbf{F_k})},\quad (8)$$

for$k$ = 1,…, *K*. According to SLNR criterion, the precoding metric$\mathbf{F_k}$is designed on the following formula

$$\mathbf{F}_k^{\mathrm{opt}} = \arg\max_{\boldsymbol{F_k}\in\mathbb{C}^{N\times L}}\mathrm{SLNR}_k \quad (9)$$

With $\mathrm{T}_r(\mathbf{F}_k^H\mathbf{H}_k^H) = \boldsymbol{L}$ for limiting power. Since $\mathbf{H}_k^H\mathbf{H}_\mathrm{k}$ is Hermitian and semidefinite and$M/L\,\sigma^2\mathbf{I}+\bar{\mathbf{H}}_k^H\overline{\boldsymbol{H}_k}$ is also Hermitian but, definite positive, by generalized eigenvalue decomposition (GED), a variable matrix exists, such that $\mathrm{T}_k \in \mathbb{C}^{N\times N}$

$$\mathbf{T}_k^H\mathbf{H}_k^H\mathbf{H}_\mathrm{k}\mathbf{T_k} = \mathbf{A_k} = \mathrm{diag}(\alpha_1,\ldots,\alpha_N) \quad (10)$$

$$\mathbf{T}_k^H(M/L\,\sigma^2\mathbf{I}+\bar{\mathbf{H}}_k^H\overline{\boldsymbol{H}_k})\mathrm{T}_k = \mathbf{I}_N \quad (11)$$

with $\alpha_1 \geq \alpha_2 \geq \cdots \geq \alpha_N \geq 0$. The columns of T_k and diagonals of $\boldsymbol{A_k}$ generalized eigenvectors and eigenvalues of pair $[\boldsymbol{H}_k^H\boldsymbol{H}_k, M/L\,\sigma^2\boldsymbol{I}+\bar{\boldsymbol{H}}_k^H\overline{\boldsymbol{H}_k}]$, respectively.
Optimal precoder metric can be given by:

$$\boldsymbol{F}_k^{opt} = \rho\boldsymbol{T}_k[\boldsymbol{I}_L;\mathbf{0}], \quad (12)$$

Where ρ is factor such that$\mathbf{T}_r(\mathbf{F_k}\mathbf{H}_k^H) = L$. The maximized resultant SLNR value is given by $\mathrm{SLNR}_k^{max} = \sum_{i=1,}^{L}\alpha_i/L$ [7]. Along with this, receiver side is also applied, denoted as $\mathbf{G}_\mathrm{k} = (\mathbf{H}_\mathrm{k}\mathbf{F_k})^H$ which results in interference free signal.

C. PRE-CODER DESIGN

Simultaneous diagonalization in general form is stated and draws a significant distinction from the original GED based deduced in (10) and (11). So, the specific algorithm of precoder $\mathbf{F}_k'$ for number of transmittersk is:

Input:

$$\boldsymbol{A_k} = \boldsymbol{H}_k^H\boldsymbol{H}_k$$

And, $\boldsymbol{C_k} = (\boldsymbol{H}_k^H\boldsymbol{H}_k + M/L\,\sigma^2\boldsymbol{I} + \bar{\boldsymbol{H}}_k^H\overline{\boldsymbol{H}_k})$

1) Compute Cholesky decomposition on$\mathbf{C_k}$, as$\boldsymbol{C_k} = \boldsymbol{G_k}\boldsymbol{G}_k^H$, where $\boldsymbol{G_k} \in \mathbb{C}^{N\times N}$ is a lower triangular matrix with positive diagonals. Then, $\mathbf{G}_k^{-1}$can be easily obtained and we have $(\mathbf{G}_k^{-1})^H = \boldsymbol{Q}_k$.

2) Compute $\mathbf{A}_k' = \mathbf{Q}_k^H\boldsymbol{A_k}\boldsymbol{Q_k}$, then compute ED on $\mathbf{A}_k'$as $\mathbf{A}_k'\boldsymbol{U_k} = \mathbf{U}_\mathrm{k}\mathbf{A_k}$. We must note that $\boldsymbol{U_k}$ must be unitary and it can also be obtained by computing the left singular matrix of $\mathbf{A}_k'$in terms of singular value decomposition (SVD).

3) Calculate $\boldsymbol{P_k} = \mathbf{U}_\mathrm{k}\mathbf{Q_k}$.

Output: $\mathbf{F}_k' = \boldsymbol{\gamma}\boldsymbol{P_k}(\mathbf{I}_L;\mathbf{0})$.

$\mathbf{F}_k'$and matched decoder $\mathbf{G}_k'$, at the receiver side can be designed as

$$\mathbf{F}_k' = \boldsymbol{\gamma}\boldsymbol{P_k}[\mathbf{I}_L;\mathbf{0}], \quad \mathbf{G}_k' = (\mathbf{F}_k'\mathbf{H}_\mathrm{k})^H \quad (13)$$

In which $\boldsymbol{\gamma}$is a normalization factor so that $\mathrm{T}_r(\mathbf{F}_k'\mathbf{F}_k'^H) = \boldsymbol{L}$.Hence, it can be established that $\boldsymbol{G}_k'\boldsymbol{H}_k\boldsymbol{F_k}$ gives a diagonal matrix, resulting in free of inter-user-interferences.

III. *PERFORMANCE METRICS*

Here the performance of the proposed system under various scenarios and parameters has been discussed. The errorperformance and capacity analysis will be done. The results of SLNR-Max precoding technique has been compared with zero-forming beamforming (ZFBF) technique for underwater acoustic channels. Scenarios are taken on the basis of number of transducers at the buoy station.

TABLE 1: Simulation Parameters

Parameter(s)		**Value**
Environment		*Rayleigh Channel*
Scenario 1	Transmitters at BS (nt)	1
Scenario 2	Transmitters at BS (nt)	2
Scenario 3	Transmitters at BS (nt)	4
Scenario 4	Transmitters at BS (nt)	6

Scenario 5	Transmitters at BS (nt)	8
Scenario 6	Transmitters at BS (nt)	10
Scenario 6	Transmitters at BS (nt)	12
Modulation type		QPSK
SNR per bit		0 to 20dB

IV. *SIMULATION RESULTS*

Figure 5 shows the simulated BER performance of the SLNR-Max precoding technique under different mentioned scenarios. Here, nt denotes the number of transducers/hydrophones employed at buoy station. It is evident from the result that there is significant gain in SNR (dB) as we move to greater number of transducers/hydrophones. There is atleast 2 dB of gain in each scenario at 10^{-4} BER level.

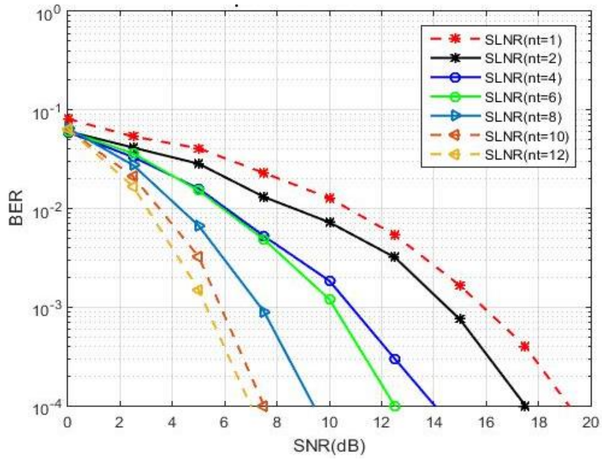

Figure 5: BER Performance of SLNR-Max for Massive MIMO in underwater acoustic communication

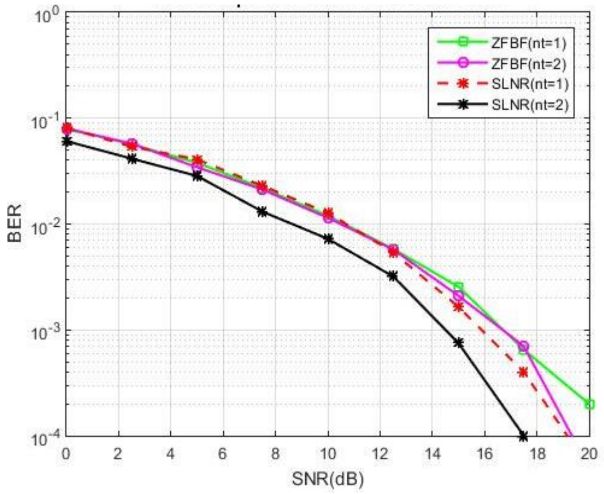

Figure 6: Comparison of BER between ZFBF and SLNR-Max Precoding of Massive MIMO for underwater acoustic communication.

Figure 7 shows the capacity performance and compares both the techniques side by side. SLNR technique yields around 90kbps with number of transducers being 2, in same scenario with ZFBF capacity is slightly less at 80kbps. Also, increasing the number of transducers to 5, higher data rates is achieved of up to 145kbps, at same diversity, ZFBF is shown to achieve less data rate of about 118kbps.

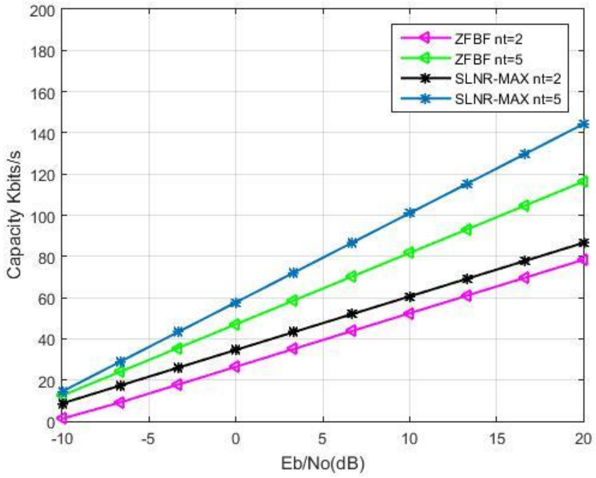

Figure 7: Capacity plot of ZFBF and SLNR-Max for Massive MIMO in underwater acoustic communication.

IV. *CONCLUSION*

We proposed a robust mechanism for underwater acoustic communication to achieve high data rate and efficient and low BER. Massive MIMO offers robust improvements over conventional acoustic mechanism [8]. Increasing the number of hydrophones/transducers results in significantly higher data rate than current conventional techniques.

The measured BER using SLNR-Max precoding techniqueQPSK carrier modulation was 10^{-2} BER at 10 dB using no diversity, 10^{-3} at 10 dB with diversity having 6 transducers and 10^{-4}at 7 dB with diversity having 10 transducers . These characteristics allow for the implementation of unmanned underwater vehicles (UUV) in real time remote control with compressed video and sound or access to internet from a submarine.

SLNR-Max precoding technique further improves the performance over more conventional ZFBF precoding, providing significant gains both in capacity and efficiency in BER with low power consumption.

Further developments into even more efficient Pre-coding techniques like dirty paper coding (DPC) can improve the performance even more. Though, DPC is more complex to implement, but the work has been going on to implement it in the system.

REFERENCES

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, “Challenges for efficient communication in underwater acoustic sensor networks,” ACM SIGBED Review, vol. 1, number 1, July 2004.

[2] J.-H. Cui, J. Kong, M. Gerla, and S. Zhou, “The challenges of building scalable mobile underwater wireless sensor networks for aquatic applications,” Special issue of IEEE Network on Wireless Sensor Networking, vol. 20, number 3, pp. 12–18, May-June 2006.

[3] M. Stojanovic, J. Preisig, “Underwater acoustic communication channels: propagation models and statistical characterization”, IEEE Commun. Mag., vol. 47, pp. 84-89, Jan. 2009.

[4] B. Lawal, Syed Saad Azhar Ali, Azlan Bin Awang,” Massive mimo systems for underwater acoustic communications”, 2016 IEEE 6th International Conference on Underwater System Technology: Theory and Applications.

[5] Zhao, Xueyuan, and Dario Pompili. “AMMCA: Acoustic massive mimo with carrier aggregation to boost the underwater communication data rate”, 10th International Conference on Underwater Networks and Systems, p. 5. ACM, 2015.

[6] Peng Cheng, Meixia Tao, and Wenjun Zhang, “A new SLNR-based linear precoding for downlink multi-user multi-stream mimo systems,” IEEE Communications Letters, vol. 14, number 11, pp. 1008-1010, November 2010

[7] G.M. Sadek, A. Tarighat, and A. H. Sayed, “A leakage-based precoding scheme for downlink multi-user MIMO Channels,” IEEE Trans. Wireless Commun., vol. 6, number 5, pp. 1711–1721, May 2007.

[8] Fredrik Rusek, Daniel Persson, Buon Kiong Lau, Erik G. Larsson, Thomas L. Marzetta, Ove Edfors, and Fredrik Tufvesson,” Scaling up MIMO: opportunities and challenges,” IEEE Signal Processing Magazine, pp. 40-60, December 2012.

[9] P. Chengsheng, Liangchen Jia, Ruiyan Cai, and Y. Ding, “Modeling and simulation of channel for underwater communication network,”International Journal of Innovative Computing, Information and Control 8, number 3 (2012): 2149-2156.

[10] Geng, Xueyi, and Adam Zielinski. “An eigenpath underwater acoustic communication channel model”, In OCEANS'95. MTS/IEEE. Challenges of Our Changing Global Environment. Conference Proceedings., vol. 2, pp. 1189-1196. IEEE, 1995

[11]Heidemann, J., Stojanovic, M. and Zorzi M. (2012) “Underwater sensor networks: applications, advances and challenges” Royal Society, Philos Transact A Math Phys Eng Sci, pp.158-75.