Capacity Analysis of MIMO Hydrophone in Underwater Acoustic Communication

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Abstract— Underwater acoustic communication is a technique of sending and receiving message below water. There are several ways of employing such communication but the most common is using hydrophones. A hydrophone is a microphone designed to be used underwater for recording or listening to underwater sound. Multiple hydrophones can be arranged in an array so that it will add the signals from the desired direction while subtracting signals from other directions. In this paper we study the gain brought by hydrophone array on underwater acoustic communications.

Keywords— UnderWater Acoustic channel (UWA); MIMO model; Hydrophone array; Capacity analysis.

I. INTRODUCTION

The past three decades have seen a growing interest in underwater acoustic communications. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. The field of underwater acoustic communication is growing rapidly because it plays in many military and commercial applications. Among these are disaster prevention, pollution monitoring and oceanographic data collection. Typical physical carriers for underwater communication signals are electromagnetic waves, optical waves and acoustic waves. Electromagnetic waves are affected by high attenuation in water (especially at higher frequencies), thus requiring high transmission power and large antennas [1, 9, 7]. Therefore, electromagnetic waves are generally used for underwater communications over very short ranges (up to 10 meters) [4]. Optical waves enable high data rate communications (in the order of a few Gbit/s) [6], but are rapidly scattered and absorbed in water, leading again to short-range communications [5]. Acoustic waves, instead, may enable communications over long-range links since they suffer from relatively low absorption. This has contributed to making acoustic transmission the most common underwater communication technique since World War Two [2, 8]. Still, Underwater Acoustic (UWA) communications are severely affected by high path loss, noise, multipath, high and variable propagation delay and Doppler spread. The combined effect of these phenomena causes the UWA channel to be temporally and spatially variable. This limits the available bandwidth and makes it dramatically dependent on both range and frequency. Short-range systems that operate over several tens of meters may have more than 100 kHz of bandwidth, while long-range systems that operate over several tens of kilometers may have bandwidths of only a few kHz. Therefore, UWA communication system mostly have low bit rates, which are in the order of tens of Kbit/s. A hydrophone array is made up of a number of hydrophones placed in known locations. These hydrophones maybe placed in a line on the seafloor, moored in a vertical line in the water column, or towed in a horizontal line behind a boat or ship, for example. Sound arriving at the array from a distant source, such as a submarine, will reach each hydrophone at slightly different times, depending on the direction from which the sound is coming. This time difference is known as the time-of-arrival-difference and can be turned into a direction. Using this information from all the hydrophones in the array, the direction from which the sound is coming can be pinpointed. Even a simple array consisting of only two hydrophones can give the approximate direction from which a sound is coming. People do this all the time in air with a "receiving array" that consists of two ears. Sound arriving from a source, such as a person speaking, will reach each ear at slightly different times, depending on the direction from which the sound is coming, making it possible for the listener to tell the direction to the speaker. When the listener wants to detect a single specific sound, hydrophone arrays are much better than single hydrophones. This is because the array is able to filter out noise coming in from all directions and focus on sounds arriving from a specific direction. The increased signal to noise ratio allows sounds that normally couldn't be detected by a single hydrophone to be heard. If a hydrophone array is being used to receive a specific sound source, it also allows the source to be quieter and still be detected.

II. UNDERWATER ACOUSTIC CHANNEL CHARACTERISTICS

Depending on their range, underwater acoustic communication links can be classified as very long, long, medium, short and very short [8]. Acoustic links can also be roughly classified as vertical and horizontal according to the direction of the sound ray with respect to the bottom. Propagation characteristics of the links vary considerably on multipath spreads, time dispersion and delay variance. The literature typically refers to shallow water as water with depth lower than 100 m, while deep water is used for deeper [3]. Below, we provide a detailed discussion of the factors that influence UWA communications. These include:

A. Path loss

Path loss is mainly caused by two phenomena, the first is attenuation which is mainly provoked by absorption due to conversion of acoustic energy into heat, which increases with distance and frequency. It is also caused by scattering a reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface). Water depth plays a key role in determining the attenuation [10]. The second is Geometric Spreading which is refers to the spreading of sound energy to a larger surface as a result of the expansion of the acoustic waves. It increases with the propagation distance and is independent of frequency. There are two common kinds of geometric spreading: spherical, which occurs when acoustic waves spread spherically outward from a source in an unbounded medium, which characterizes deep water communications, and cylindrical, which occurs when acoustic waves spread horizontally because of a medium which has parallel upper and lower bounds; the latter typically characterizes shallow water communications [11].

B. Noise

Acoustic noise in underwater communication channel can be either natural ambient noise or Man-made noise. The latter is mainly caused by machinery noise (pumps, reduction gears, power plants, etc.), and shipping activity (hull fouling, animal life on hull, cavitation), especially in areas encumbered with heavy vessel traffic, while the former is related to hydrodynamics (movement of water including tides, current, storms, wind, rain, etc.), seismic and biological phenomena [12].

C. Multi-path

Multi-path propagation may be responsible for severe degradation of the acoustic communication signal, since it generates Inter-Symbol Interference (ISI). The multi-path geometry depends on the link configuration [13, 14]. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have extremely long multi-path spreads. The extent of the spreading is a strong function of depth and the distance between transmitter and receiver.

D. High delay and delay variance

The propagation speed in the UWA channel is five orders of magnitude lower than in the radio channel. This large propagation delay (0.67 s/km) can reduce the throughput of the system considerably [15]. The very high delay variance is even more harmful for efficient protocol design, as it prevents from accurately estimating the round trip time (RTT), which is the key parameter for many common communication protocols.

E. Doppler spread

The Doppler frequency spread can be significant in UWA channels, causing a degradation in the performance of digital communications. Transmissions at a high data rate causing many adjacent symbols to interfere at the receiver, requiring sophisticated signal processing to deal with the generated ISI [16]. The Doppler spreading generates two different effects on signals: a simple frequency translation, which is relatively easy for a receiver to compensate for, and a continuous spreading of frequencies which constitutes a non-shifted signal, which is more difficult for a receiver to compensate for.

Most of the described factors are caused by the chemical-physical properties of the water medium such as temperature, salinity and density, and by their spatiotemporal variations. These variations, together with the wave guide nature of the channel, causing the acoustic channel to be temporally and spatially variable. In particular, the horizontal channel is by far more rapidly varying than the vertical channel, in both deep and shallow water [17].

III. UNDERWATER ACOUSTIC MIMO CHANNEL MODEL

A MIMO underwater acoustic channel model like a wave guide consisting of the water between two half spaces: air and water-bed. The assumption are generally well mixed and very small increase in pressure as we go deeper into the water. A MIMO underwater acoustic channel structure with N_t transmitter hydrophones and N_r receiver hydrophones. On the transmitter and receiver sides, each hydrophone pair has a constant vertical separation of Δz_t and Δz_r respectively. The transmitter and receiver depths z_t and z_r. The MIMO array is placed in vertical direction so as to maximize the delay spread difference between each sub-channel and thus minimize the resulting spatial correlation [18]. The MIMO channel is modelled by $N_t \times N_r$ sub-channels, the transfer function of sub-channel connecting hydrophone m ∈ [1, N_t] to hydrophone n ∈ [1, N_r] denoted $H_{mn}(f)$ can be derived from the following equation:

$$H_{mn}(f) = \sum_{p=0}^{p-1} \frac{r_p}{\sqrt{A(d_{p,mn}, f)}} e^{-i2\pi f \tau_{p,mn}} \tag{1}$$

Where r_p is the total reflection loss for a path p with s surface and b bottom reflections which is equal to

$$r_p = (r^{+}. L_{ss}) . (r^{-}. L_{sb}) \tag{2}$$

Where r^{+} is attenuation coefficient due to reflections on the surface only and is relatively small in magnitude because of the impedance mismatch between the water and air. If the sea water is calm and still with no turbulence, reflection coefficient generally tends to perfect reflection value 1. But if the sea surface is rough (due to waves), a loss would be incurred for every surface interaction. Let this loss be modelled by a constant coefficient L_{ss} which is absorption loss at sea surface [19]. On the bottom, the coefficient reflection varies according to the impedance variation. Such coefficient estimation can be obtained using Rayleigh reflection law:

$$r^{-} = \left| \frac{\frac{\rho 1}{\rho} \cos\Theta - \sqrt{(c/c1)^2 - sin^2\Theta}}{\frac{\rho 1}{\rho} \cos\Theta + \sqrt{(c/c1)^2 - sin^2\Theta}} \right| \tag{3}$$

where ρ and ρ1 are density of water and bottom respectively, c and $c1$ are sound speed in water and bottom respectively while Θ is the angle of incidence of the reflected wave that can be computed from the following equation, if the reflection from surface:

$$\Theta_s = tan^{-1}\left(\frac{L}{2bD + z_t - (N_t + 1 - 2m)\frac{\Delta z_t}{2} - (z_r - (N_r + 1 - 2n)\frac{\Delta z_r}{2})}\right) \tag{4}$$

If the reflection from bottom:

$$\Theta_s = tan^{-1}\left(\frac{L}{2bD - (z_t - (N_t + 1 - 2m)\frac{\Delta z_t}{2}) + z_r - (N_r + 1 - 2n)\frac{\Delta z_r}{2}}\right) \tag{5}$$

Additional reflection losses due to rough or absorbing bottom is modeled by a constant coefficient L_{sb} . $d_{p,mn}$ Is the distance of the signal transmission along the *p* path of sub-channel *mn* and $\tau_{p,mn} = d_{p,mn}/c$. $A(d_{p,mn}, f)$ is the sum of spreading and absorption loss:

$$A(d_{p,mn}, f) = k. 10 \log d_{p,mn} + d_{p,mn} .10 \log \alpha(f) \tag{6}$$

Where *k* is the spreading factor depending upon the geometry of propagation (its commonly used values are *k* = 2 for spherical spreading, *k* = 1 for cylindrical spreading and *k* = 1.5 for all practical spreading). A α (*f*) referred as the absorption coefficient which is an increasing function of frequency. The absorption loss can be expressed empirically using the Thorp's formula which gives α (*f*) in dB/km for frequency *f* in kHz. For *f* >400 kHz, the Thorp's formula:

$$\alpha(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 . 10^{-4} f^2 + 0.003 \tag{7}$$

For lower frequencies, the formula becomes:

$$\alpha(f) = 0.002 + 0.11 \frac{f^2}{1+f^2} + 0.011 f^2 \tag{8}$$

Hence now, the whole MIMO hydrophone array channel is represented by the following $N_t \times N_r$ channel matrix:

$$H_{mn}(f) = \begin{bmatrix} H_{11}(f) & \cdots & H_{N_t 1}(f) \\ \vdots & \ddots & \vdots \\ H_{1N_r}(f) & \cdots & H_{N_t N_r}(f) \end{bmatrix}$$

IV. CAPACITY COMPUTATION OF HYDROPHONE ARRAY IN UWA CHANNEL

The hydrophone array channel capacity gives the maximum data transmission rate that can be reliably transmitted through UWA communications channel. The general expression for hydrophone array capacity:

$$\mathrm{C} = \sum_{i=0}^{r-1} \left(1 + \frac{SNR}{N_t} \lambda_i\right) \tag{9}$$

Where SNR is the signal to noise ratio, λ_i is the Eigen values of H_{mn} with $0 \le i < \mathrm{r}$ where r is the rank of H_{mn}, since the right part of the above expression is similar to a SISO capacity, hence the Hydrophone array capacity can be viewed as a sum of *r* SISO capacities. The advantages of hydrophone array capacity depends on matrix H_{mn}, the larger the rank and Eigen values H_{mn} have, the more hydrophone array capacity we can generate [20, 21].

V. NUMERICAL ANALYSIS

Figure 1 provides numerical evaluation of capacities over the above considered UWA channel. Capacity is drawn for the SISO, 2x2 hydrophone array and 4x4 hydrophone array configurations as a function of SNR. We can observe that the capacity gain is larger for the MIMO hydrophone array architecture as compared to the SISO architecture. As an example for SNR = 18 dB, UWA channel capacity for the SISO is about 5.9 bits/s/Hz while for 2x2 hydrophone array it is found to be around 10.7 bits/s/Hz and 18.2 bits/s/Hz for 4x4 hydrophone array. Thus it represents a maximum 4x4 MIMO hydrophone array data transmission rate of 218.4 Kbits/s and 128.4 Kbits/s for 2x2 MIMO hydrophone array with the chosen bandwidth of 12 kHz. Therefore it clearly shows that the 4x4 MIMO gain is about 208.47 % more than SISO gain thus exhibiting that the UWA capacity is increasing linearly with min(N_t,N_r). As a consequence, larger gains could be achieved by increasing the number of hydrophones in the transmitter and receiver side.

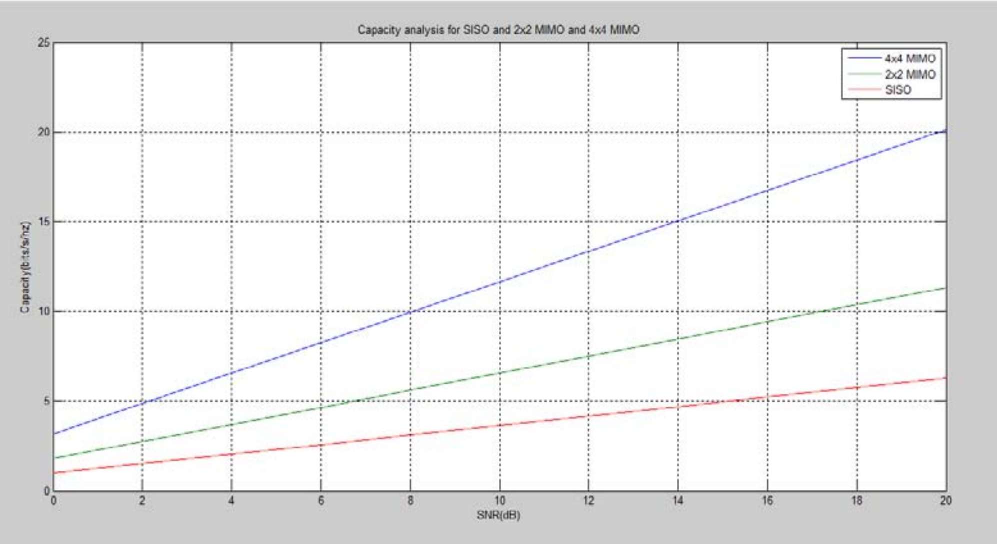

Figure 1. Capacity analysis for SISO, 2x2 MIMO and 4x4 MIMO

Figure 2 shows MIMO hydrophone array and SISO capacities as function of communication range for a fixed SNR of 18 dB. The graph shows that both SISO and MIMO hydrophone array UWA capacities decrease when the value of communication range D increases and also stated phenomenon is a definitive feature that distinguishes an underwater acoustic system from a terrestrial radio communication system: UWA channel capacity is strongly dependent on the transmission distance. Nonetheless one can observe that MIMO hydrophone array UWA capacity fades more rapidly than the SISO UWA capacity thus indicating that the frequencies to be used in MIMO transmission have to be carefully selected as a function of the desired communication range.

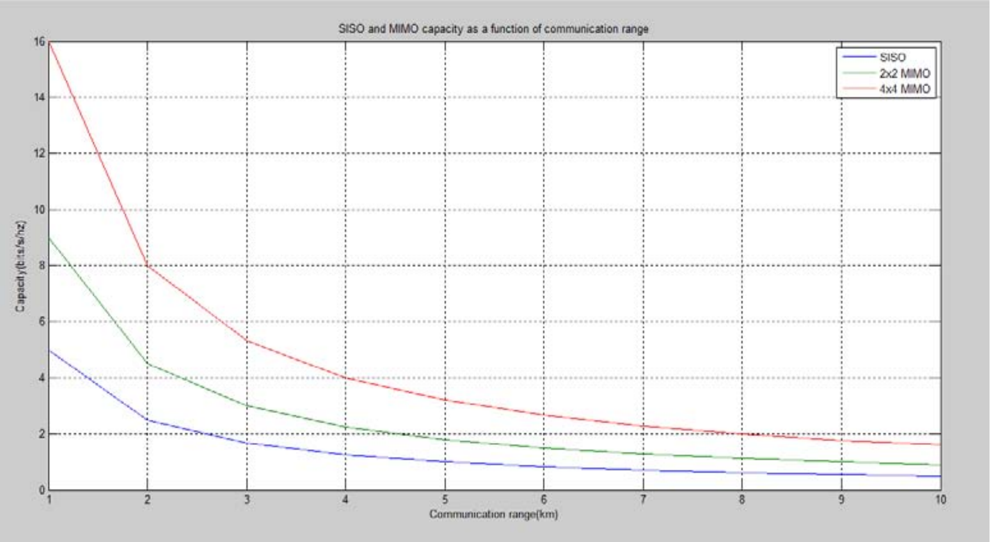

Figure 2. SISO and MIMO capacity as a function of communication range

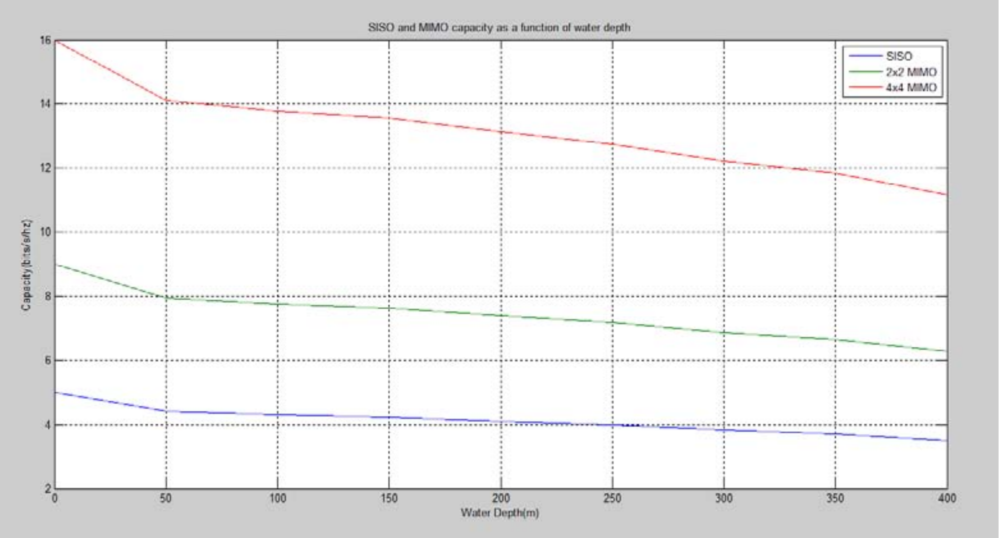

Figure 3. SISO and MIMO capacity as a function of water depth

Figure 3 shows the MIMO hydrophone array and SISO capacity results for varying values of water depth. We can observe that MIMO hydrophone array capacity gain is slowly decreasing with an increase is water column depth. The largest gain is observed for very shallow water (≤30 m). This decrease in MIMO hydrophone array capacity gain with increasing depth is easily explained by the fact that MIMO capacity is strongly associated with the correlation between sub-channels which is mathematically represented by matrix determinant of H_{mn}. The lowest spatial correlation is observed for a rich multipath environment which occurs when the water depth of the channel is very shallow.

VI. CONCLUTION:

The primary aim of this paper was to quantify and predict the gain brought by MIMO hydrophone array for underwater acoustic communication. Our paper provides a model of the MIMO hydrophone array underwater acoustic channel taking into consideration all the underwater dominant disturbances. A numerical evaluation of the underwater channel capacity is then used which leads to an accurate approximation of the maximum achievable data transmission rate for an underwater communication parameters. Extensive simulation results for several transmission parameters and channel configuration show the expected MIMO hydrophone array gain is significant and the capacity increase is in the same order as that of wireless transmission. Our analysis has also demonstrated some restrictions on frequencies, communication range as well as underwater environment have to be made in order to ensure that MIMO hydrophone array capacity gain is maximum. With the above capacity based approach, our paper depicts a simple means to provide an upper bound on the expected MIMO hydrophone array gain in the field of underwater acoustics and forms a useful tool in designing and optimizing future MIMO hydrophone array underwater communication system.

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