# uwMIMO-HARQ: Hybrid ARQ for Reliable Underwater Acoustic MIMO Communications

Mehdi Rahmati and Dario Pompili
Department of Electrical and Computer Engineering
Rutgers University–New Brunswick, NJ, USA
E-mails:{mehdi_rahmati, pompili}@cac.rutgers.edu

## ABSTRACT

Achieving robust and reliable data communications in the harsh underwater environment is still a challenging issue due to the fast-changing and unpredictable nature of the acoustic channel. Notwithstanding the use of acknowledgement messages at the link layer, data transmission protocols still require more efficient error control strategies so to achieve a higher link reliability. A novel solution based on hybrid automatic repeat request (HARQ) is proposed that exploits the diversity gain offered by independent links in an underwater acoustic Multiple Input Multiple Output (MIMO) system. Irrespective of the channel regime, the proposed scheme aims at reducing the probability of retransmission and at increasing the link reliability via packet-level codeword selection and waterfilling coding. Encoding and decoding algorithms at the transmitter and receiver, respectively, are designed, multiple evaluation metrics are defined, and computer-based simulation results are presented to quantify the performance improvement of the proposed methods.

## Keywords

Underwater acoustic networks; MIMO; ARQ; Spatial diversity.

## 1. INTRODUCTION

**Overview:** Over the past few years, underwater communications and networks have attracted the attention of researchers and engineers due to the wide range of applications they enable such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance, just to name a few [1]. Achieving reliability in data transmission is a major issue in every communication systems; this is especially true in harsh media like the underwater acoustic environment. Specifically, the time- and frequency-varying acoustic channel suffers from several impairments such as frequency-dependent attenuation, non-Gaussian and non-white noise, long and variable propagation delays as well as multipath and fading. The temporal and spatial variability of the acoustic channel as well as its limited available bandwidth – which is bounded by the high transmission loss above 100 KHz and by the high environment noise below 10 KHz – are dependent on both range and frequency [1].


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And yet, for distances above a hundred of meters, adopting acoustic technology is the only way to transmit data underwater wirelessly. Hence, underwater acoustic networks necessitate for more efficient error control strategies so to achieve a higher link reliability and, consequently, a higher net data rate. Using a large number of antennae in a Multiple Input Multiple Output (MIMO) configuration brings forward novel opportunities to increase simultaneously reliability and spectral efficiency of underwater communication systems. In MIMO systems, spatial diversity refers to the number of *independent* links of the channel; exploiting such diversity by multiplexing data on multiple streams leads to a much higher reliability in comparison with single-antenna solutions at the price of a higher, yet affordable, complexity and cost. Such physical-layer data multiplexing – with no additional power expenditure – increases the transmission net data rate of a system with the same bandwidth [2].

**Related Work:** Automatic repeat request (ARQ) [3] is a conventional error-control transmission technique that uses acknowledgement messages [4, 5]; if the received packet is not error free and if the error is detectable, the transmitter is notified with an appropriate message to retransmit the same packet until the receiver confirms its successful reception. ARQ can be combined with Forward Error Correction (FEC) so to reduce the number of retransmissions; as a result, such synergistic combination can overcome bad channel conditions and increase link reliability. This coding method is called hybrid ARQ, i.e., HARQ [3]. Specifically, in HARQ type-I every (re)transmitted packet conveys the same information, i.e., error detection and FEC; this method is called *Chase Combining* (CC). Conversely, instead of retransmitting the same data as HARQ type-I does, type-II exploits *Incremental Redundancy* (IR) and retransmits extra information as a complement to the data contained in previous packets. By doing that, HARQ type-II, which is appropriate for time-varying and noisy channels, increases the coding reliability; however, it requires more memory, which is used as buffer at both sides of the communication in order to store the currently progressing packets. Generalized HARQ type-II [6] exploits high-rate punctured convolutional codes. Authors in [7] introduced HARQ with selective combining in fading channels and showed that their solution outperforms the generalized HARQ as it combines the advantages of both type-I- and type-II-ARQ schemes. In [8], fountain codes were applied to HARQ in underwater networks in order to minimize the number of retransmissions. Authors in [9] suggested an adaptive coding based on IR-HARQ to improve the packet error rate in underwater acoustic networks. Implementation of an underwater HARQ on real nodes was discussed in [10]. Despite the work done in this area, there is still a need to develop more robust and effective schemes for underwater acoustic communication systems, specially in large MIMO structures, which are suitable to support high data-rate multimedia traffic.

**Motivation and Contribution:** Classical physical- and link-layer communication techniques often fail in providing the required robustness and reliability underwater due to the unpredictable nature of the underwater acoustic channel. For this reason, our goal is to reduce the number of costly packet retransmissions and find a smart solution that considers the channel condition and leads to a more effective coding structure. To this end, we propose a novel MIMO-based hybrid ARQ scheme, called *uwMIMO-HARQ*, that exploits the high diversity gain offered by a multiple-antenna MIMO system. Considering different channel conditions, defined as *channel regimes*, we reduce the probability of retransmission and increase the link reliability thus maximizing the net data rate. The main contributions of this paper are listed below:

- A novel MIMO-HARQ scheme is proposed for the harsh underwater acoustic environment;
- Encoding and decoding algorithms that are tailored for the underwater environment at the transmitter and receiver, respectively, are designed;
- A packet-level codeword selection and a waterfilling coding technique are presented to allocate codes that adapt to the varying underwater acoustic channel regime.

**Paper Outline:** The remainder of the paper is organized as follows. Section 2 defines the problem, presents the underwater acoustic MIMO system model, and proposes mathematical expressions for the underwater acoustic channel regimes. Section 3 focuses on the design of the proposed encoding and decoding algorithms as well as on the codeword selection and waterfilling technique. Section 4 presents performance results of our solution and shows comparisons against the conventional HARQ scheme. Finally, Sect. 5 concludes the paper.

# 2. SYSTEM MODEL

In this section we model an underwater acoustic MIMO system and define the underwater acoustic channel regimes.

## 2.1 Underwater Acoustic MIMO System

Let us assume a MIMO underwater acoustic system with $N_T$ transmit and $N_R$ receive antennae. The configuration of our proposed system is depicted in Fig. 1, in which surface buoys are shown with a long bar equipped with multiple antennae. If $N_T > N_R$, i.e., the number of antennae at the buoy is significantly greater than at the receiver, and a large number of antennae are used over active terminals, then we can name this structure as *large MIMO system*. In practice, it can be assumed that the receiver has many antennae in the case of a surface buoy, or a limited number in the case of Autonomous Underwater Vehicles (AUVs). Under such assumption, a multiple-antenna communication system can improve both the reliability and the net data rate; however, because of multipath, channel fading occurs, which usually deteriorates the system performance due to Inter-Symbol Interference (ISI) between data packets traveling on different paths. Fading is called *slow* when the coherence time of the channel, i.e., the time duration over which the channel impulse response can be considered to be not varying, is larger than the delay constraint of the channel; otherwise, it is called *fast*. Obviously, having Channel State Information (CSI) is precious at both communication sides if the channel changes slowly. However, in a fast-varying scenario, the channel coefficients change several times during each transmission round, which makes it difficult to acquire updated CSI, even at only the receiver.

The underwater channel impulse response can be assumed to have a *natural sparse structure* as it often consists of a limited

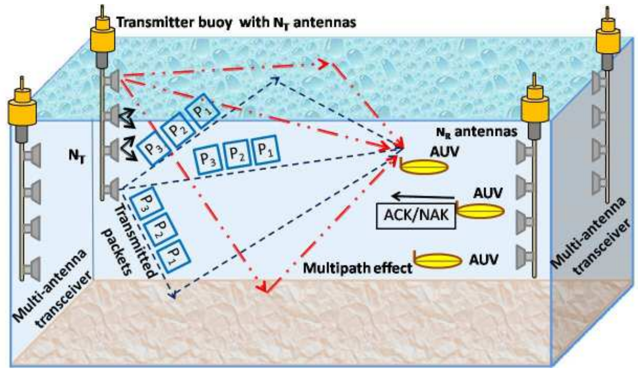


**Figure 1: Configuration of the proposed MIMO system, where $N_T$ and $N_R$ are the number of transmit and receive antennae, respectively, $P_i' s; \forall i = 1, 2, 3, ...$ are the coded transmitting packets, and ACK/NAK denotes positive or negative acknowledgements of the reception of a packet.**

number of dominant non-zero coefficients. The equivalent low-pass time-variant impulse response between the $j^{th}$ transmit antenna and the $i^{th}$ receive antenna is expressed by,

$$h_{ij}(\tau;t) = \sum_{p=1}^{P} a_{ij}^{p}(\tau;t) \exp(-j2\pi f_c \tau_{ij}^{p}(t)) \delta(t - \tau_{ij}^{p}(t)), \quad (1)$$

where $t$ is the time variable, $\tau$ is the delay, $a_{ij}^p(\tau;t)$ is the channel attenuation factor between antenna $j$ and $i$ in the $p^{th}$ path, $2\pi f_c \tau_{ij}^p(t)$ represents the channel phase for the $p^{th}$ path, in which $\tau_{ij}^p(t)$ is the path-dependent time-varying delay, and $f_c$ is the carrier frequency. Hence, in a more compact form, $\mathbf{H}(\tau;t)$ is the $N_R \times N_T$ time-varying channel matrix, which is defined as,

$$\mathbf{H}(\tau;t) = \begin{bmatrix} h_{11}(\tau;t) & h_{12}(\tau;t) & \dots & h_{1N_T}(\tau;t) \\ h_{21}(\tau;t) & h_{22}(\tau;t) & \dots & h_{2N_T}(\tau;t) \\ \vdots & \vdots & & \vdots \\ h_{N_R1}(\tau;t) & h_{N_R2}(\tau;t) & \dots & h_{N_RN_T}(\tau;t) \end{bmatrix}. \quad (2)$$

The received signal at the $i^{th}$ antenna is expressed as,

$$\begin{aligned} y_i(t) &= \textstyle\sum_{j=1}^{N_T} \int_{-\infty}^{\infty} h_{ij}(\tau;t) x_j(t-\tau) d\tau + z_i(t) \\ &= \textstyle\sum_{j=1}^{N_T} h_{ij}(\tau;t) * x_j(\tau) + z_i(t), \quad i = 1, 2, ..., N_R, \\ &= \textstyle\sum_{j=1}^{N_T} \sum_{p=1}^{P} \int_{-\infty}^{\infty} a_{ij}^p(\tau;t) \exp(-j2\pi f_c \tau_{ij}^p(t)) x_j(t - \tau_{ij}^p(t)) d\tau \\ &\quad + z_i(t), \quad i = 1, 2, ..., N_R, \end{aligned} \quad (3)$$

where $x_j(\tau)$, $j = 1, ..., N_T$, is the transmitted signal from the $j^{th}$ transmit antenna, $z_i(t)$ is assumed to be a zero-mean Gaussian background noise with variance $\sigma_{z_i}^2$, and the asterisk $(*)$ represents the convolution operation. For the sake of compactness, (3) can be rewritten in matrix form as,

$$\mathbf{y}_{N_R \times 1}(t) = \mathbf{H}(\tau;t) * \mathbf{x}_{N_T \times 1}(\tau) + \mathbf{z}(t). \quad (4)$$

Sound propagation underwater is influenced by many factors such as channel path loss, background noise, multipath effect, Doppler spread, and high and variable propagation delay [1]. Considering temperature, salinity, and pressure of the body of water traversed, the sound speed may vary between 1450 and 1540 m/s; as a consequence, small changes in the sound speed may lead to significant changes in the sound propagation [11]. Furthermore, sound reflection from the surface and bottom as well as from other objects in the ocean and also sound refraction are the causes for the heavy multipath effect underwater, which is the result of the spatial variability of the sound speed, both in depth and location [12]. The multipath geometry relates to the channel configuration, e.g., vertical channels are characterized by a small time dispersion, whereas horizontal channels may have extremely long multipath spreads depending on the water depth [1]. In this paper, we model the underwater acoustic channel as in [11,12], i.e.,

$$A(l,f) = A_0 l^k a(f)^l, \tag{5}$$

where $A(l,f)$ is the path loss, $f$ [KHz] is the frequency, $l$ [Km] is the distance, $k$ is the spreading factor, $A_0$ is a scaling factor, and $a(f)$ [dB/Km] is the absorption coefficient, which is modeled as $0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75\times10^{-4}f^2 + 0.003$ [11].

When considering multiple propagations through the linear acoustic channel, in which the signal at the receiver is the superposition of several delayed versions of the original signal, each following different paths, the Channel Transfer Function (CTF) of each path can be modeled as $H_p(f) = \Gamma_p/\sqrt{A(l_p,f)}$, where $\Gamma_p$ is the cumulative reflection coefficient. Therefore, the overall CTF with multipath between the $j^{th}$ transmit and the $i^{th}$ receive antenna is calculated as $H_{ij}(f) = \sum_p H_p(f)e^{-j2\pi f\tau_p}$, in which $\tau_p$ represents the propagation delay associated with path $p$.

From a MIMO perspective, the most important issue to consider in (3)-(4) is the spatial and temporal correlation between channel coefficients, which affects the decoding performance in terms of capacity and error probability. We assume that the links are independent and that the spacing criteria between the antenna elements is met. In this case, exploiting a MIMO system can significantly increase the communication performance in comparison with a Single Input Single Output (SISO) system.

## 2.2 Underwater Acoustic Channel Regimes

Although there are many factors that can be considered to define the channel quality, in this paper we focus on the received Signal-to-Noise Ratio (SNR). First, we discuss its influence on the decoding performance; then, we define two types of channel regimes based on it, and exploit them in Sect. 3.

The received instantaneous symbol-level SNR, $\gamma_s$, is measured at the output of the receiver and is defined as the ratio of the signal power, $\mathcal{E}_s$, to noise power, $\sigma_z^2$, i.e., $\gamma_s = \mathcal{E}_s/\sigma_z^2$. The average SNR, $\bar{\gamma_s}$, can be calculated as $\bar{\gamma_s} = \int_0^\infty \gamma_s f(\gamma_s)d\gamma_s$, where $f(\gamma_s)$ denotes the Probability Density Function (PDF) of $\gamma_s$. To deal with receiver diversity, let us assume that we use Equal Gain Combining (EGC) at the receiver; under this assumption, $\gamma_s$ can be expressed as a combination of the individual channel SNRs [13]. We conclude that, in a system with $P$ paths combined at the receiver, the SNR at a receiver $i$ can be computed as,

$$\gamma_{s_i} = \sum_{j=1}^{N_T}\sum_{p=1}^{P}\gamma_{s_{jp}}, = \frac{\sum_{j=1}^{N_T}\sum_{p=1}^{P}\left|a_{ij}^p\right|^2}{\sigma_{z_i}^2}. \tag{6}$$

In Selection Combining (SC), which is the lower complexity combining method [13], the combiner chooses the path with the strongest SNR and outputs it to the threshold decision device. In an underwater communication system, with centralized transmit and receive antennae, the strongest path is often the Line Of Sight (LOS) link; thus, we can conclude that,

$$\gamma_{s_i} = \frac{\sum_{j=1}^{N_T}\left|a_{ij}^{LOS}\right|^2}{\sigma_{z_i}^2}, \tag{7}$$

where $a_{ij}^{LOS}$ is the channel attenuation factor between antenna $j$ and $i$ in the LOS path.

Inspired by [2] and applying the Chernoff bound, the average symbol error rate $\bar{P}_{eMIMO}$ can be upper bounded as follows,

$$\bar{P}_{eMIMO} \leqslant \bar{N}_e \prod_{i=1}^{d.o.}\left(\frac{1}{1+\bar{\gamma_s}d_{min}^2/4N_T}\right), \tag{8}$$

where $\bar{N}_e$ is the number of nearest neighbors, $d_{min}$ is the minimum distance between constellation points in a modulation with order (size) $M$, $d.o. = N_T N_R$ stands for the maximum diversity order, and $\bar{\gamma_s}$ is the average received SNR per single-antenna channel.

Based on the received SNR, we can define two types of acoustic channel regimes, a *well conditioned* and a *ill conditioned*.

**Well-conditioned Regime:** The diversity order, d.o., is calculates as the number of independent channel links and may vary from $N_R N_T$ to $N_R$ [14]. It can be expressed asymptotically as,

$$\lim_{\bar{\gamma_s}\to\infty}\frac{\log(\bar{P}_e)}{\log(\bar{\gamma_s})} = -d.o., \tag{9}$$

where $\bar{P}_e$ is the average error probability as a function of the average SNR, $\bar{\gamma_s}$. In good channel conditions, i.e., at high SNRs, a MIMO system can achieve a diversity order of $d.o. = N_T N_R$ and obtain a low error probability approximately equal to $\bar{P}_e \approx (\bar{\gamma_s})^{-d.o.}$ [15]. Therefore, the higher the diversity order, the better the link reliability in terms of error probability. It is worth mentioning that the average probability of symbol error rate is highly affected by the modulation scheme, transceiver structure, and channel quality (i.e., channel regime). When the channel is unknown at the transmitter, which is a common case underwater as the high propagation delay and limited bandwidth make CSI exchange problematic, when not unfeasible, the upper bound of the error can be defined as in [2], i.e.,

$$\bar{P}_{eMIMO} \leqslant \bar{N}_e\left(\frac{\bar{\gamma_s}d_{min}^2}{4N_T}\right)^{-d.o.}. \tag{10}$$

Now, by comparing a multiple-antenna system with a single-antenna one, where $\bar{P}_{eSISO} \leqslant \bar{N}_e(\frac{4}{\bar{\gamma_s}d_{min}^2})$, we can easily extract the diversity gain achieved by using a multiple-antenna system.

**Ill-conditioned Regime:** In practice, when the received SNR is low such that the d.o. is less than $N_T N_R$, the effective diversity is calculated by measuring the slope of the error rate versus the SNR at each point [16]. Such slope is smaller than at high SNRs (where the maximum d.o. is obtained) and is expressed as,

$$d.o. = -\frac{\partial\log(\bar{P}_e)}{\partial\log(\bar{\gamma_s})} = -\bar{\gamma_s}\frac{\partial\log(\bar{P}_e)}{\partial\bar{\gamma_s}} = N_T N_R\frac{\frac{-d_{min}^2}{4N_T}}{1+\frac{\bar{\gamma_s}d_{min}^2}{4N_T}}(-\bar{\gamma_s}). \tag{11}$$

Eq. (11) denotes the worst case for the diversity order – as we extract it from the upper bound of the error probability –, which is a fraction of the maximum d.o. (i.e., $N_T N_R$). In practice, in the low-SNR regime, it is essential to monitor the *outage probability*, $P_{out}$, in order to ensure that the SNR does not fall below a certain specified threshold, $\gamma_{th}$, at each received antenna, i.e., $P_{out} = P[\gamma_{max} = \max(\gamma_1,\gamma_2,...,\gamma_{N_T}) \leqslant \gamma_{th}]$.

# 3. UNDERWATER MIMO-HARQ

In this section, we introduce and elaborate the main idea behind our HARQ technique for underwater MIMO systems. Specifically, in Sect. 3.1, we discuss our proposed encoding and decoding algorithms to combat the unreliability issue in SISO channels. In Sect. 3.2, we present the block diagram of the proposed system, and detail the decision architectural blocks used at the receiver including hybrid combining and codeword selection. In Sect. 3.3,

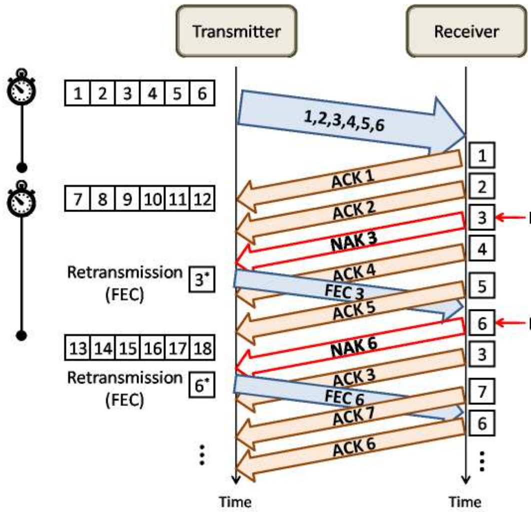


**Figure 2: Conventional HARQ type-II selective repeat scheme, where packets are labeled with ID numbers and $\star$ denotes the extra data to implement Forward Error Correction (FEC) of previous packet at the receiver. A timer keeps the round-travel time and triggers a retransmission if a time-out occurs. Here, packets $3$ and $6$ are erroneous and the transmitter is instructed via a NAK to retransmit the required information.**

we propose a packet-level codeword selection to choose the correct packet out of all the received ones, and discuss how our uwMIMO-HARQ scheme can adapt to the specific channel regime via a novel waterfilling coding technique. Finally, in Sect. 3.4, we extract the reliability efficiency of the system; under some realistic assumptions, retransmission rate as well as error probability are calculated.

## 3.1 Encoding and Decoding Algorithms

Figure 2 depicts the basic concept of conventional Hybrid ARQ type-II. When the event of sending a packet is activated, data is combined with the appropriate error detection code and header. Packet is stored in a buffer until an ACK arrives after the packet was successfully decoded at the receiver [5]. Otherwise, a NAK message requests extra information, i.e., FEC codes, which will be transmitted in the next round in order to avoid the whole codeword retransmission. This packet is shown by a star $(^*)$ in the figure. As an example, let us assume that packets 3 and 6 are erroneous, and that the receiver is not able to recover them. The transmitter is then informed via a NAK message and the next transmission round is performed. Note that in ill-conditioned channels the number of retransmissions will increase, which reduces the net link data rate.

Using the same example, Fig. 3 illustrates our uwMIMO-HARQ scheme, which is more reliable than the conventional method. By exploiting MIMO channel diversity, it requires fewer retransmissions as it considers multiple replicas of the packet at the receiver, which increases the probability of packet acceptance. In noisy/bursty channels, where all the packets are lost or not recoverable, retransmission is done as last resort, as shown in the figure for packet $6^*$. Differently from the previous case illustrated in Fig. 2, packet $3^*$ has now an acceptable copy at the receiver and passes the error control process, thus increasing the channel utilization efficiency.

Algorithm 1 presents the pseudo-code procedure at the transmitter. Let us assume that we have enough memory at both sides of the communication system and that we transmit $u$, a k-bit data, in a codeword $x = (f(u), u)$ via a $(n, k)$ Error Detecting Code (EDC)

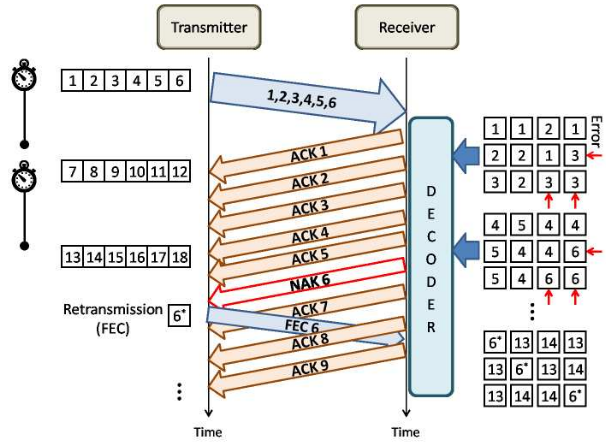


**Figure 3: Proposed uwMIMO-HARQ type-II selective repeat scheme to reduce the probability of retransmission, where received packets and their copies are shown at the receiver. Here, packets $3$ and $6$ are erroneous; however, packet $3$ has an acceptable copy and passes the error control process, whereas packet $6$ is detected as erroneous and needs retransmission.**

**Algorithm 1** Encoding: uwMIMO-HARQ at Transmitter

**Input:** $x : data\ stream\ u$
**Output:** $codeword\ x\ and\ x^*$

```
Wait for event()
if Event(request to send) then
    while time-out codeword() do
        Step I:
        for length of Tr_Buffer do
            Get data; make packet(n,k)(); store packet()
            Send packet x_j to multiple-antenna coder for antenna j; start timer()
        end for
    end while
end if
if Event(Arrival notification) then
    Receive packet+waterfilling data()
    Change (n,k)_j if requested
    if Acknowledgment is ACK then
        Purge packet and stop timer()
    else
        Acknowledgment is NAK
        if previously original packet was sent then
            Make and send FEC()
        else
            Resend the packet()
        end if
        if event time-out then
            Goto Step I for retransmission
        end if
    end if
end if
```

$C_0$ [3]. Error Correction Coding (ECC) is performed on codeword $x^*$, which is defined as $x^* = (f(q(u)), q(u))$. Here, $q(u)$ is a k-bit error-correcting code on $C_0$ and is generated by codeword $(q(u), u)$ based on an error-correction code $C_1$, which conventionally is an invertible half-rate $(2k, k)$ code. Let us assume now that $\tilde{x} = (\tilde{f}(u), \tilde{u})$ and $\tilde{x}^* = (\tilde{f}(q(u)), \tilde{q}(u))$ represent the received codewords corresponding to $x$ and $x^*$, respectively [3], and that the sequence number remains the same in the transmission or retransmission of a codeword. When the acknowledgment arrives after a round-trip delay, packet $x$ is purged from the buffer.

Algorithm 2 reports the receiver's operation of error control of the proposed system. As discussed earlier, the maximum number of packets the receiver takes is less than or equal to the diversity order, $d.o.$, of the MIMO system. Meanwhile, HARQ decoding is performed and packet-level codeword selection is exploited, as discussed in Sect. 3.3. The general structure and a block diagram of the proposed system are presented in the following section.

**Algorithm 2** Decoding: uwMIMO-HARQ at Receiver

**Input:** $\tilde{x}\ and\ \tilde{x}^*$
**Output:** $U,\ ACK/NAK,\ waterfilling$

```
Wait for event()
if Event(Arrival notification) then
    for Maximum packets=d.o. do
        Receive and store packet()
    end for
    for Length of Re_Buffer do
        HARQ decoding()
    end for
    Packet-level codeword selection using majority voting()
    if Error detected AND not NAK sent before then
        Store NAK()
    else
        Store ACK()
    end if
    Waterfilling decision()
    Send packet+waterfilling data()
    Purge packet
end if
```

## 3.2 Coder and Decoder Design

Figure 4 represents the transmitter-receiver block diagram of the proposed MIMO system. HARQ coder in the transmitter contains EDC, ECC, and waterfilling coding information. The FEC version is stored in the buffer, but the error-detecting coded stream is sent to the multiple-antenna coder after passing through a Serial-to-Parallel (S/P) block. Space-time code is a well-known multiple-antenna coder that has been introduced in [17] to provide redundancy in space and time so to achieve full transmit diversity and coding gains. It is an extra processing step that is performed prior to the transmission over multiple antennae without knowledge of the channel state. As the underwater channel is a multipath medium, the transmitted packets are received from $N_T P$ paths at every receiver antenna. The first block at the receiver side performs a Hybrid Combining (HC) for every antenna. This method is called *Generalized technique* in [13] as it is a tradeoff between the two extreme combining approaches discussed earlier, i.e., Equal Gain Combining (EGC) and Selection Combining (SC). This scheme offers lower complexity in comparison to a pure EGC/MRC receiver. First, SC chooses the $N_T$ most significant signals among the $N_T P$ ones that have the largest SNR; then, EGC combines the $N_T$ signals corresponding to the $N_T$ transmitter antennae. A total of $N_R$ resulting signals are then decoded by the multiple-antenna decoder, and the packets enter the HARQ decoding block. After error control processing and waterfilling decision, a packet contains the appropriate ACK/NAK message, which is sent back to the transmitter.

## 3.3 Codeword Selection and Waterfilling

In order to combat the effect of ill-conditioned channels, when all the codewords are infected by error or when the number of correct codewords is equal to the number of undetectable codewords, first, we categorize the duplicated packets. Afterwards, a low-complexity and fast error-control technique is exploited to make the best decision on the packets. If there exists at least one correct codeword out of multiple copies, the process is done; otherwise, we need a decision method to compare the erroneous codewords. For this purpose, we follow the simple, yet effective, *majority voting* approach. This is a low-complexity technique based on the assumption of the largest number of occurrences of a codeword. In this

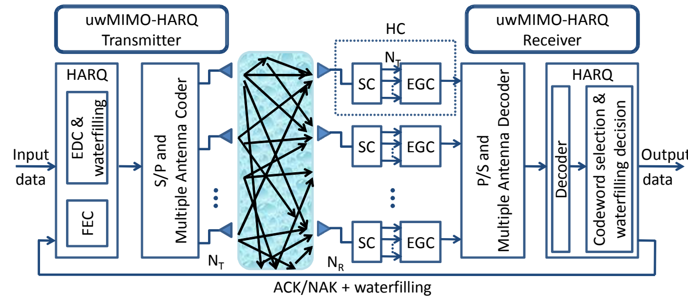


**Figure 4: Block diagram of *uwMIMO-HARQ*, where S/P is the Serial-to-Parallel block at the multiple-antenna coder, SC denotes the selection combining method (which chooses the $N_T$ strongest signals, i.e., only one path out of the $P$ available multipaths for each independent link), EGC represents the equal gain combination of $N_T$ signals. Note that HC is the hybrid combining technique, which is a combination of SC and EGC. Finally, EDC and FCE are the error detection and correction codes, respectively.**

method the number of codewords must be odd [18]. Let $\tilde{x}_i,\ i = 1, ..., d.o.$ be multiple codewords, then $\tilde{x}_{maj} = Maj(\tilde{x}_1, ..., \tilde{x}_i)$ outputs their average correlation. Note that, although this technique is not optimal and there may be some errors in the decision making, this is the least complex and fastest method we can use to meet the strict delay requirement imposed by the receiver.

To further enhance the coding performance, we propose a waterfilling coding technique in which, instead of using power budgeting and waterfilling to compensate for the destructive effect of the channel, we change the coding strength of each link based on their condition. In other words, based on the output of majority voting, in ill-conditioned or well-conditioned channels additional information can be extracted to help characterize each link. This information is fed back to the transmitter along with the ACK/NAK packet so to strengthen the code for specific low-quality links. Different conditions that lead to the retransmission are discussed below.

## 3.4 Link Throughput Efficiency

Let $P_c$ be the probability of correct reception of codeword $\tilde{x} = (\tilde{f}(u), \tilde{u})$, $P_d$ be the probability of detecting error in codeword $\tilde{x}$, and $P_{ud}$ be the probability of undetectable error, i.e., the error that is not detectable using current error detection. Let $P_a = P_c + P_{ud}$ be the acceptance probability; the ratio $\mathcal{E}_a = \frac{P_{ud}}{P_a}$ determines the *acceptance error*, which is a performance measure of link reliability. Obviously, the smaller the acceptance error ratio, the higher the reliability. We calculate $P_c$ as,

$$P_c = 1 - (P_d + P_{ud}) = (1 - \bar{P}_{eMIMO})^{\frac{n}{log_2 M}}. \quad (12)$$

We consider a Reed-Solomon code $(n, k, q)$ with minimum distance $d_{min.code}$, where the probability of undetectable errors is calculated as in [19],

$$P_{ud}(\epsilon) = \sum_{i=d_{min.code}}^{n} \binom{n}{i} \sum_{j=0}^{i-d_{min.code}} (-1)^i \binom{i-1}{j} \times 2^{i-d_{min.code}-j} \epsilon^i (1-\epsilon)^{n-i}, \quad (13)$$

where $\epsilon$ is the bit error rate probability and binary coding with $q = 2$ is assumed.

Let $m_c$, $m_d$, and $m_{ud}$ be the number of replicas of each codeword packet; they represent the number of correct codewords, detectable codewords, and undetectable codewords, respectively. We

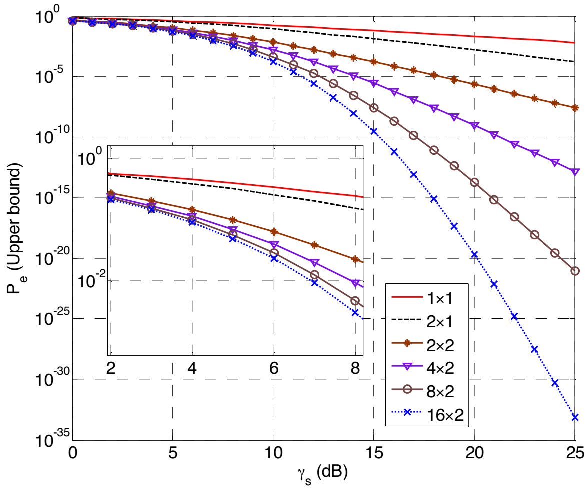


**Figure 5: Average symbol error rate vs. Signal-to-Noise Ratio (SNR) for different numbers of antennae in an underwater MIMO system.**

define *link throughput efficiency* as follows [3],

$$\eta = \frac{1}{I_r}\left(\frac{k}{n}\right), \tag{14}$$

where $I_r$ is the average number of transmissions including original, FEC transmission, and retransmission.

To analyze the throughput efficiency at the link level, we consider three conditions, as detailed below.

- **Condition I:** When no error is detected in the codewords or the errors are detectable, i.e., $m_c > 0$, $m_d \geq 0$, and $m_{ud} = 0$. In this case, at least one codeword is correct; therefore, there is no need for retransmission (FEC transmission) and $I_r^{(I)} = m_c P_c + m_d P_d$.
- **Condition II:** When we have two types of correct codewords, i.e., $m_c \geq 0$, $m_d \geq 0$, and $m_{ud} > 0$. If $m_c \neq m_{ud}$, we use majority voting; hence, there is no need for retransmission and $I_r^{(II)} = m_c P_c + m_d P_d + m_{ud} P_{ud}$. If $m_c = m_{ud}$, a retransmission will be needed; in this case, $I_r^{(II)} = m_c P_c + m_d P_d + m_{ud} P_{ud} + m_{c(FEC)} P_{c(FEC)} (1 - P_c)$.
- **Condition III:** When all the codewords contain errors that are detectable, i.e., $m_c = m_{ud} = 0$ and $m_d \geq 0$; in this case, FEC request is necessary and $I_r^{(III)} = m_d P_d + m_{c(FEC)} P_{c(FEC)} (1 - P_c)$.

# 4. PERFORMANCE EVALUATION

Results based on computer simulations are provided to evaluate the performance of uwMIMO-HARQ in different settings and also in comparison with conventional HARQ. Specifically, we first discuss the simulations assumptions; then, we present the gain from using a MIMO system underwater; finally, we plot the improvements of our HARQ mechanism with respect to conventional HARQ.

**Simulation Assumptions:** We consider an underwater MIMO system with a variable number of antennae, in which the distance between transmitter and receiver is between 5 and 15 Km, and the frequency can be changed in the range $0.1 - 20$ KHz. The modulation scheme adopted is BPSK and the coding technique used is Reed-Solomon $(34, 32)$ (unless otherwise specified).

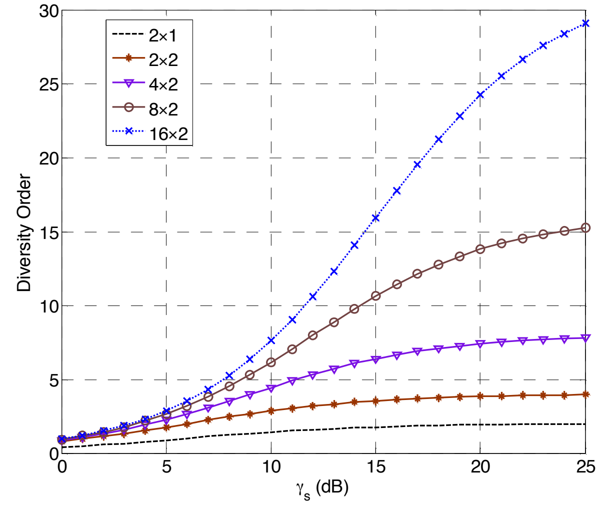


**Figure 6: Diversity order vs. SNR for different numbers of antennae. *Well-conditioned* channel regime is the range of high SNRs where the diversity order approaches the value of $N_T N_R$. *Ill-conditioned* regime is the range of SNR in which the diversity order drops.**

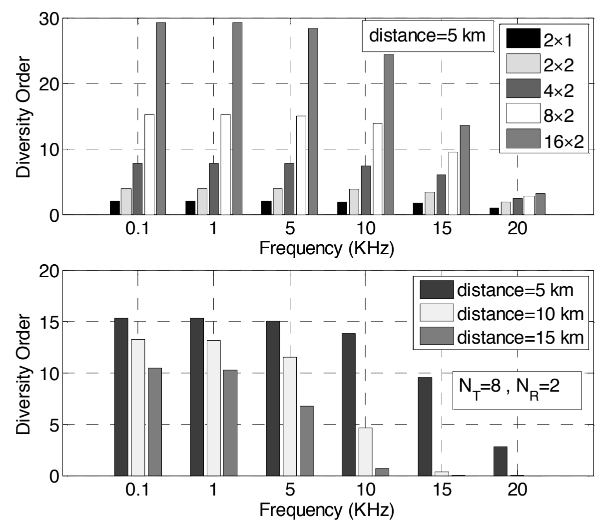


**Figure 7: Effect of frequency and link distance on the performance of the system for a fixed distance and varying number of antennae (upper sub-figure) and for a fixed number of antennae at different distances (bottom sub-figure).**

**Underwater MIMO:** Fig. 5 represents the effect of changing the number of antennae on the average symbol error rate versus different levels of received SNR. By increasing the number of antennae, we achieve better error probability. Note that, as expected, the diversity gain is much higher in a well-conditioned regime, i.e., high SNRs, than in a ill-conditioned regime as the diversity order decreases when the average SNR reduces, as explained in Sect. 2.2. Figure 6 compares the achieved diversity order in different MIMO structures considering a varying number of antennae. It is apparent that, for well-conditioned regimes, as the SNR increases, the diversity order asymptotically approaches the value of $N_T N_R$. The range of well-conditioned regime is proportional to the number of

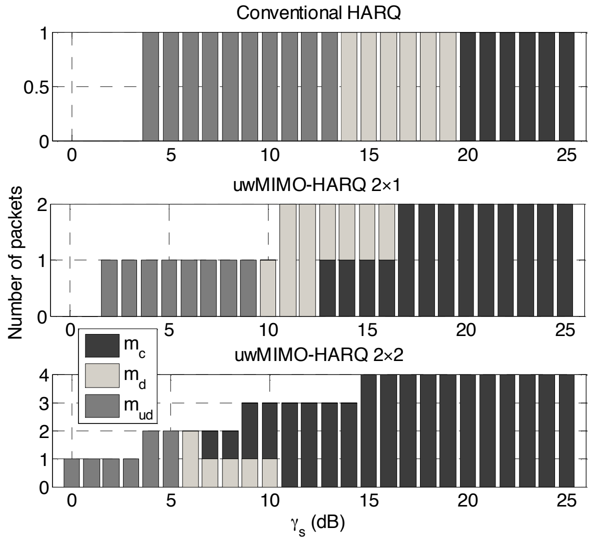


**Figure 8: Number of correct codewords, $m_c$, detectable erroneous codewords, $m_d$, and undetectable erroneous codewords, $m_{ud}$, at the output of the decoder for different underwater MIMO designs in comparison with conventional HARQ.**

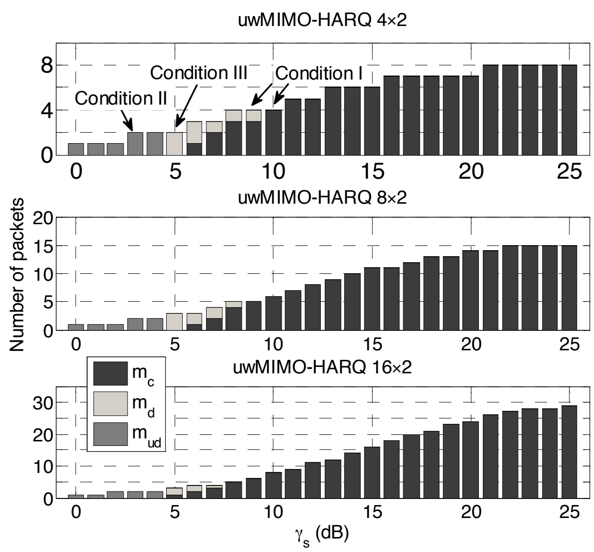


**Figure 9: Number of correct codewords, $m_c$, detectable erroneous codewords, $m_d$, and undetectable erroneous codewords, $m_{ud}$, for different underwater MIMO designs with a large number of transmitted antennae. Different channel conditions are presented in the top sub-figure.**

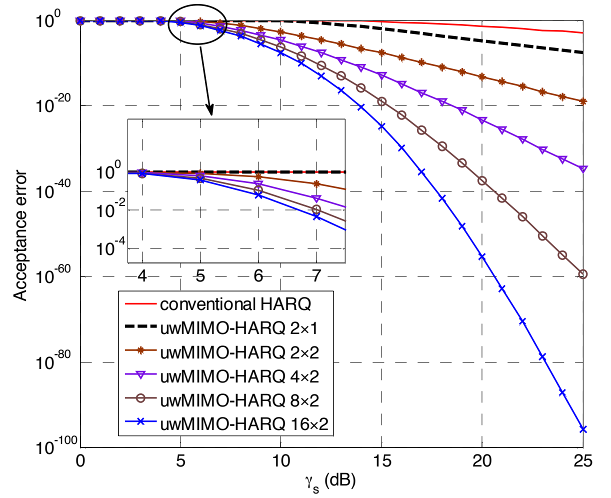


**Figure 10: Acceptance error, $\mathcal{E}_a$, of our uwMIMO-HARQ (using different settings) in comparison with conventional HARQ.**

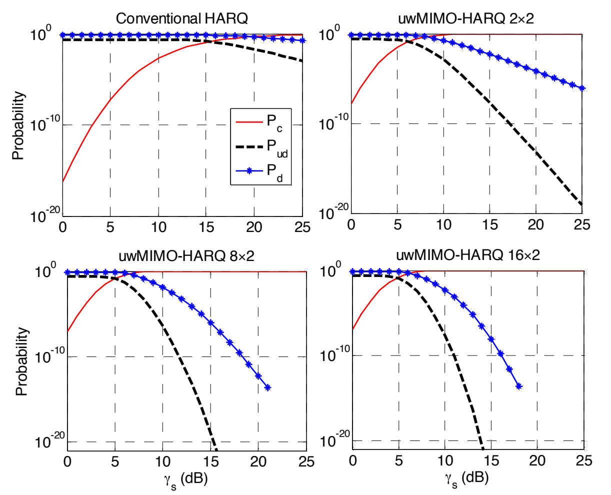


**Figure 11: Probabilities of correct reception, $P_c$, of detecting error, $P_d$, and of undetectable error, $P_{ud}$, in different underwater MIMO designs and in conventional HARQ.**

antennae. Moreover, as the diversity order depends on the received SNR, it is severely affected by the underwater channel condition. In Fig. 7, the effect of frequency and link distance is presented, assuming a fixed transmitted signal power. The upper sub-figure corroborates that, for a given channel distance, the diversity order drops as the frequency increases. This behavior is the same for all values of $N_T N_R$. Furthermore, it is shown in the bottom sub-figure that the increase in the transmitter-receiver distance leads to a reduction in diversity order, in all investigated frequencies.

**uwMIMO-HARQ:** In Figs. 8 and 9, the number of different possible detected packets, $m_c$, $m_d$, and $m_{ud}$, at the output of the proposed decoder is presented. In the conventional HARQ method, where only one copy of the transmitted packet is available at the receiver, correct reception starts from high received SNRs, i.e., 20 dB in this figure, which is a high and often unrealistic target for underwater communication systems. Below this value, but not lower than 14 dB, the packet is detected as erroneous and a NAK requesting the appropriate FEC is sent. Therefore, the retransmission request occurs if the SNR ranges in $14-19$ dB. For SNRs lower than that, although the correct packet is not received, the conventional decoder cannot even detect the error and the incorrect packet is accepted as if it were correct.

In our proposed uwMIMO-HARQ technique, where the number of available copies of the packet is equal to the diversity order, these SNR boundaries decrease proportionally to the number of transmit and receive antennae, thus increasing the reliability of the communication link. It is apparent in these figures that undetected erroneous packets are accepted for SNRs lower than 10 dB in $2\times1$

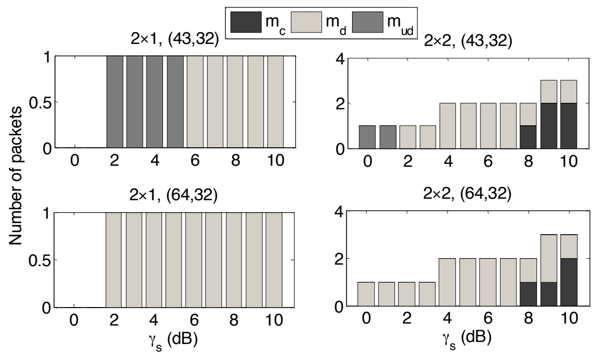


**Figure 12: Waterfilling technique for low SNR regimes for different MIMO designs when two Reed-Solomon codes are used, i.e., (43,32) and (64,32).**

system, 6 dB in $2 \times 2$ system, and 5 dB in $4 \times 2$, $8 \times 2$, and $16 \times 2$ systems. Besides, the FEC transmission is requested when none of the copies is detected as the correct packet, which will happen for $SNR \in (9, 13)$ dB in $2 \times 1$ system, $SNR \in (5, 7)$ dB in $2 \times 2$, and $SNR \in (4, 6)$ dB in $4 \times 2$ and $8 \times 2$ designs. The last sub-figure shows that in a $16 \times 2$ system, for all SNR levels considered, there are several redundant copies that are accepted and so FEC is not required. This property makes our proposal particularly well-suited for large MIMO systems. It is concluded that the probability of retransmission decreases at the expenses of providing redundant replicas, even more than we need. Thus, in a well-conditioned regime, instead of sending too many packet replicas, in a large MIMO structure we dedicate a fraction of antennae to send different packets; as a result, rate improvement can be achieved.

Figure 10 represents the acceptance error of uwMIMO-HARQ as a measure of reliability. For a SNR lower than 5 dB, the system is unreliable for all structures; however, as the SNR increases, the acceptance error drops, making the system more reliable. The curves verify that uwMIMO-HARQ achieves a higher level of link reliability than the conventional method, and its reliability increases proportionally to the number of antennae. In Fig. 11, the proposed system is compared with the conventional method in terms of $P_c$, $P_{ud}$, and $P_d$. The probability of undetectable error in uwMIMO-HARQ starts to fall at lower SNRs in comparison with the conventional method, and the reduction in slope of the curve increases in higher-order MIMO structures. The probability of correct reception passes the two other probabilities at lower SNRs in uwMIMO-HARQ. Finally, Fig. 12 shows how the proposed waterfilling technique works in low SNRs. Note that, increasing the strength of the code – e.g., using a (43,32) or even a (64,32) Reed-Solomon code – leads to a higher number of detectable packets and thus to an enhanced link reliability.

# 5. CONCLUSIONS

We proposed a coding scheme based on Hybrid ARQ type-II, called uwMIMO-HARQ, to increase communication reliability for underwater acoustic channels. This technique benefits from the diversity gain offered by Multiple Input Multiple Output (MIMO) systems. Thanks to a better use of the replicas of each transmitted packet, the probability of correct reception increases and, consequently, the probability of retransmission decreases. We also designed a packet-level codeword selection and a waterfilling technique to adapt coding strength to the underwater channel condition.

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