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Review article

MIMO-OFDM underwater acoustic communication systems—A review

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The ever increasing demand for bandwidth, efficiency, spatial diversity and performance of underwater acoustic (UWA) communication has opened doors for the use of Multi-Input Multi-Output (MIMO). A combination of MIMO and Orthogonal Frequency Division Multiplexing (OFDM) has proved to be a promising solution for many scenarios in UWA communication; on the contrary, it also amplifies the design challenges for implementing such schemes to acquire the required bandwidth efficiency. The goal of this study is to provide a comprehensive survey of the latest researches in the field of UWA MIMO-OFDM communication. The previous works are summarized, reviewed and compared according to their years of publication while problems faced by UWA MIMO-OFDM communication are highlighted. The articles are classified according to the focused techniques like channel estimation, equalization, coding and detection. Furthermore the works are compared based on the complexity and performance of the algorithms while some future research issues are identified.

Contents

1. Introduction

Electromagnetic and optical waves propagate poorly in sea water which leaves acoustic signaling as the only viable option for long-range underwater communication. Underwater acoustic (UWA) channel is unique, compared to radio communication channels, because of many distinctive features, where limited bandwidth has been the most significant one which drives the algorithm design for UWA communication [1]. Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) solves the limited bandwidth problem to some extent but making multipath as the most prominent concern to be taken care of while designing a UWA communication model, as MIMO communication has multiple channels between transmitters and receivers with each signal containing data from all the transmitters and thus simultaneous estimation of all the channels is required [2].

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MIMO-OFDM in underwater acoustics is relatively a new research field. Though in radio communication networks, MIMO-OFDM had been used since last 2 decades but in underwater communication networks, it has been introduced in recent past and researchers have proposed many different transmission schemes to improve data rates and reduce bit error rates. Though MIMO-OFDM has numerous benefits however the challenges being faced while implementing such systems are also crucial, which makes MIMO-OFDM system design an intricate job [3,4].

OFDM is considered as a low-complexity alternative to single-carrier modulation for the next generation of acoustic modems. To mitigate the bandwidth limitation, the use of multicarrier modulation is introduced in the UWA communication, which puts an end to the long-time delays in underwater acoustic channels. OFDM is a promising multi-carrier transmission scheme because of its robustness against multipath, frequency selective fading and inter-symbol interference (ISI) without complex equalization techniques, thus increases the spectral efficiency and data rate while making the link more reliable [5–9]. Although OFDM does not require complex equalizers, however for the smooth realization of MIMO communication to achieve higher data rates and to ensure reliability; stringent channel synchronization, estimation and equalization are required [10].

Due to the quest for efficient use of acoustic bandwidth, the use of space time methods for exploitation of spatial diversity has become a topic of interest for the researchers during recent years. MIMO is one such approach which increases the system capacity by using multiple transmitters and receivers. It differs from the traditional spatial diversity systems, where same data bits are transmitted from each transmitter while in MIMO systems each transmitter transmits different coded data, that is parallel transmission of independent data streams resulting in an improved data rate performance [11]. The combination of MIMO and OFDM is a tempting low-complexity solution for bandwidth-efficient communications over frequency selective and bandwidth limited UWA channels. It combines the benefits of spatially de-correlated acoustic channel with the frequency diversity that exists due to delay-spread, and results in considerable capacity improvement. Thus coherent MIMO-OFDM systems have been considered ideal choice for the dynamic and extremely band limited UWA channels [6,9,12,13].

In this work we review, summarize and compare different communication schemes of UWA MIMO-OFDM being modeled and tested by different researchers, starting from the initial designs and discussing the latest techniques being proposed, as to the best of our knowledge no one has given any attention to this earlier. The efficiency and effectiveness of the system depends on the overall communication system, therefore we need to discuss all the necessary details of a system in order to compare the individual techniques being used for a specific purpose. For example, we cannot compare the estimation techniques like Least Square (LS) or Minimum Mean Square Error (MMSE) for MIMO-OFDM without knowing the whole model, as the estimation scheme greatly depends on the complexity the system can afford, along with the channel being used. Therefore in some cases the LS may take priority than MMSE depending on the conditions and requirements of the system [14,15]. Although all the papers here discuss the basic steps of MIMO-OFDM communication such as coding, transmission, detection, estimation, equalization etc., focusing on a specific step more than the others, thus we categorize papers according to the focused techniques like channel estimation or equalization. The rest of the paper is organized as follows: Section 2 explains the problems being faced while designing a UWA MIMO-OFDM communication system. In Section 3, the basic UWA MIMO-OFDM system is presented while the articles explaining the MIMO-OFDM communication systems are reviewed and classified based on the channel estimation techniques, channel equalization schemes, detection algorithms and channel coding in Section 4. Finally Section 5 concludes our work.

2. Problems faced by UWA MIMO-OFDM communication

Due to the unique nature of UWA channel, UWA communication faces a lot of hurdles such as propagation loss, different types of noises, salinity, effects of environment, temperature, pressure, depth and many more factors. We will not go into the details of the problems being faced by overall underwater communication; instead we just discuss the common issues related to MIMO-OFDM systems only, which include the following:

2.1. Inter-symbol-interference

UWA communication faces a high level of multipath effect due to the reflection of signals from wavy sea surface, uneven sea-bed and numerous other obstacles inside the sea. The signals also get refracted inside the water due to variation of speed of sounds at different depths. There are four kinds of reflected signals being received at the receiver: direct path, reflected from surface only, reflected from bottom only and signals reflected from both. Although each receiver receives multiple reflected and direct signals from each transmitter, however Fig. 1 shows the idea of multipath by showing only few signals, where *Puvsb* shows the path between uth transmitter and vth receiver having s surface and b bottom reflections [16]. Thus many delayed replicas are being received at the receiver along with the direct signal, which destroys and distorts the original signal in the form of inter symbol interference (ISI) or inter block interference (IBI) [10]. The ISI depends on the time delay of the signal, the longer the delay, more the ISI. OFDM proves to reduce ISI effect to some extent by dividing the channel delay time into number of subcarriers. Furthermore, the ISI and the IBI are mitigated to some extent by using Null-Tones (NTs) and the Guard Interval (GI) redundancy of length higher than the channel size and introducing cyclic prefix (CP) and zero padding (ZP) schemes as sort of low complexity equalization schemes. This problem gets severe in case of MIMO, as there are multiple channels between transmitters and receivers; and a simultaneous transmission of data where all the signals follow multipath to reach the receiver, therefore at the receiving end, there are a lot of delayed replicas from different channels and thus more ISI [17–19].

2.2. Doppler shifts

Doppler shift is the shift in frequency due to the relative motion of the either source, receiver or both. The Doppler scaling factor a_p for θ_p incident angle of pth sound ray at the receiver is given by [20]:

$$a_p = \left(\frac{v_r}{c}\right) \cos\theta_p \tag{1}$$

where v_r denotes the transmitter/receiver speed and c is the speed of sound in water. In wireless communication the speed c of the waves is too large relative to v_r, this makes the Doppler scaling factor almost negligible, while the slower speed of sound inside water results in larger Doppler scaling factor. The Doppler frequency offsets in UWA OFDM systems are quite different in different subcarriers (i.e. non-uniform Doppler Shifts), which causes severe Inter Carrier Interference (ICI) [18]. The impact of Doppler shift can be minimized by keeping sub-carriers spacing more than the possible frequency deviation, which obviously results in degradation of spectral efficiency and data rate. Two significant and simple methods being proposed by researchers to mitigate this issue in OFDM communication systems are: using null carriers for phase synchronization and using an adaptive approach that considers phase coherence between successive OFDM blocks. In case of MIMO the compensation of Doppler shifts is rather

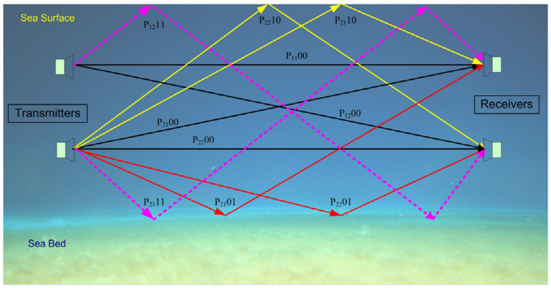

Fig. 1. Multipath effect.

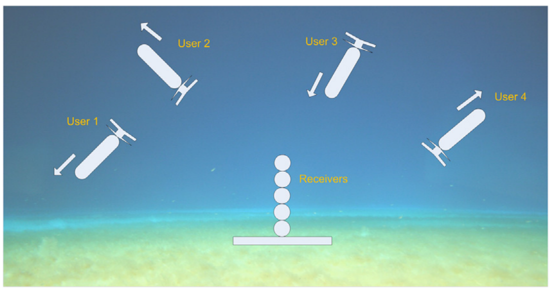

Fig. 2. Distributed MIMO system.

more significant issue because all the arriving signals at the receiver may not have the same Doppler scaling factor; different channels can have different values. Also in multiuser or distributed MIMO systems, the Doppler scaling factors are totally different for different users since users are likely to move in different directions with respect to the receivers as shown in Fig. 2 [21,22].

2.3. Peak-to-average-power ratio

The PAPR simply means the ratio of the maximum peak power divided by the average power of the signal. OFDM is known to have high PAPR due to the superposition of signals of all sub-carriers. The peak power becomes much higher than the average power due to constructive accumulation of these superimposed signals. Also transmitted OFDM signals can have high peak values in the time domain since the IFFT operation adds many subcarrier components. This high PAPR limits the efficiency of MIMO-OFDM in UWA communication by leading to saturation in the power amplifier and thus a power amplifier of high power scope is required which has low efficiency-cost factor and gives rise to non-linear distortion and superposition of the signal spectrum resulting in performance degradation [23,24]. Many PAPR reduction techniques are available for OFDM systems based on pre-coding, selective mapping method, clipping method and proper insertion of interleaves etc. [25,26].

3. UWA MIMO-OFDM system model

The basic MIMO system consists of N_t transducers and N_r receivers. The duration of overall ODFM block is given by $T' = T + T_g$, where T is the OFDM symbol duration and T_g is the guard interval. The subcarrier spacing is given by $1/T$. The kth subcarrier at frequency f_k is given by [27]:

$$f_k = f_c + k/T, \quad k = -K/2, \ldots, K/2 - 1 \tag{2}$$

where f_c denotes the carrier frequency and K denotes the number of subcarriers so that bandwidth is $B = K/T$ Let $s_u[k]$ be the encoded information symbol and $g(t)$ is the pulse shaping filter, then the signal transmitted by uth transducer is given by:

$$\widetilde{x}_u(t) = 2\mathrm{Re}\left\{\left[\sum_{k\in SA} s_u[k] e^{j2\pi \frac{k}{T}t} g(t)\right] e^{j2\pi fct}\right\} \quad t \in [0, T'] \tag{3}$$

For (v, u)th transmitter–receiver pair, the multipath channel consists of $P_{v,u}$ discrete paths and the channel impulse response is given by:

$$h_{v,u(\tau,t)} = \sum_{p=1}^{P_{v,u}} A_{v,u,p}\delta(\tau - (\tau_{v,u,p} - a_{v,u,p}t)) \tag{4}$$

where $A_{v,u,p}(t)\tau_{v,u,p}(t)$, $a_{v,u,p}$ are the amplitude, the delay and the Doppler scaling factor of the pth path of (v, u)th transmitter–receiver pair. Eq. (4) differentiates the UWA system model from the above water wireless communication model by expressing the unique UWA channel with severe Doppler and multipath effects. The passband signal at the vth receiver with the added noise $\widetilde{n}_v(t)$ is given by [27]:

$$\widetilde{y}_{v(t)} = \sum_{u=1}^{N_t} \sum_{p=1}^{P_{v,u}} A_{v,u,p}\widetilde{x}_u((1 + a_{v,u,p})t - \tau_{v,u,p}) + \widetilde{n}_v(t). \tag{5}$$

4. UWA MIMO-OFDM systems review

In this section we will discuss the papers which described the basic techniques for UWA MIMO-OFDM communication and the overall transmission schemes. The initial papers about MIMO architecture used to compare the results of MIMO-OFDM with other spatially and frequency diverse systems. The idea was introduced for the first time in 2007 when two forms of diversities were exploited [12]; the first one was frequency diversity using coded orthogonal frequency-division multiplexing (COFDM), which exploited the frequency selectivity inherent in channels that suffer from multipath propagation and second was spatial diversity using MIMO which used multiple transducers for the increase of potential capacity of the system. Though this study proved the idea of MIMO-OFDM however experimental tests have not been conducted yet [12].

The idea was experimentally proved by B. Li et al. in 2007, by transmitting QPSK mapped OFDM data from two transmitters simultaneously and using block by block processing at the receiver. Null and pilot subcarriers were introduced for the compensation of Doppler shift and channel estimation respectively. Convolutional coding (CC) or Low Density parity Check (LDPC) coding was applied and a maximum- a-posteriori (MAP) or linear zero-forcing (ZF) detector was used for MIMO demodulation on each OFDM subcarrier, where the performance of MAP detector was found better than that of the ZF detector [28]. The idea was further expanded in [29] by experimentally testing more than two transmitters and higher order modulation schemes like 8-QAM/16-QAM/64-QAM with Minimum Mean Square Error (MMSE) equalization with prior information and it was found that higher order modulation increased the spectral efficiency considerably.

After the successful trials of B. Li et al., many researchers started focusing on MIMO-OFDM and developed different transmission schemes, including work done by Y. Emre in 2008, in which a turbo-coded, PSK modulated MIMO-OFDM underwater acoustic communication model was proposed [30]. Both coherent and differential transmission schemes were used, where differential scheme eliminated the need of channel estimation by exploiting the fact that adjacent frequencies undergo almost identical fades. A soft decision aided iterative MAP algorithm was used for decoding at the receiver end, whereas MMSE detection was preferred in the coherent transmission case [30].

The problem of selection of OFDM block duration was highlighted in [31], along with the reasons effecting performance limit including conventional detection methods and the relation between number of transmitters and subcarriers in a given bandwidth. It was found that large number of transmitters resulted in performance loss with less number of subcarriers, so the number of transmitters and sub-carriers must be in proportion for better performance and bandwidth efficiency [31]. A new MIMO detector consisted of a hybrid successive interference cancellation and soft minimum mean square error (MMSE) equalization coupled with LDPC channel decoding for iterative detection on each subcarrier was designed in [32]. The receiver focused on the iterative processing between the MIMO detection and channel decoding however channel estimation and carrier synchronization were not included in the loop. The Doppler Effect was estimated and compensated using carrier offset frequencies (CFO) estimation algorithm where the energy on the null subcarriers was used as the objective function to search for the best CFO estimate. After testing with data from three different experiments, a speed of 125.7 kb/s over a bandwidth of 62.5 kHz was achieved with acceptable bit error rate [32].

The two main problems of UWA MIMO-OFDM communication: Doppler and delay spreads were explicitly focused for the first time in [4,33] and the mean square error of UWA channel estimators as a function of these spreads and thus the extreme limits of the Doppler and delay spreads, above which the signal couldn't be decoded properly, were found. The Delay Power Density Spectrum $Q_p(\tau) = Q_p(0,\tau)$ was obtained from the Delay Cross Power Spectral Density $Q_p(\xi,\tau)$ and the root mean square (rms) delay spread was given by [4]:

$$\mu_\tau = \frac{\int \tau Q_p(\tau)d\tau}{\int Q_p(\tau)d\tau}, \qquad \sigma_\tau = \sqrt{\frac{\int (\tau-\mu_\tau)^2 Q_p(\tau)d\tau}{\int Q_p(\tau)d\tau}} \tag{6}$$

$Q(\xi,\tau)$ was Fourier transformed with respect to both variables to get Doppler Cross Power Spectral Density $P_D(f,w)$, then Doppler Power Density Spectrum was obtained as $P_D(f) = P_D(f,0)$ and rms Doppler spread was given by [4]:

$$\mu_f = \frac{\int fP_D(f)df}{\int P_D(f)df}, \qquad \sigma_f = \sqrt{\frac{\int (f-\mu f)^2 P_D(f)df}{\int P_D(f)df}}. \tag{7}$$

Different extreme values for Doppler and delay spreads were measured in different weathers and environmental conditions, with different number of sub-carriers and pilot symbols, above which the signal couldn't be estimated and decoded properly [4,33].

In 2012, the MIMO-OFDM acoustic modem reached a certain level of maturity and was successfully implemented on a floating point and fixed point DSP platforms and it was found that non-binary LDPC coding performed better than the convolutional coding, at the cost of increased decoding time; and fixed point implementation drastically reduced the processing time compared with the floating-point counterpart, running at a higher clock frequency [34,35].

4.1. Channel estimation

Channel Estimation means to estimate channel parameters from the received signals. The noisy underwater channel results in signal distortion, fading and noise addition. MIMO OFDM communication is based on the assumption that all the channels between transmitters and receivers must be known and properly estimated, which is challenging because each received signal contains independent data from all the transmitters and multiple channels need to be estimated at the same time, which explains the need for the development of numerous schemes and algorithms to efficiently estimate the channels [7,36]. The basic role of the channel estimation algorithm is to estimate the value of H depending upon the values noted for $y(t)$ and $x(t)$ There are a number of channel estimation techniques being used for MIMO-OFDM; the commonly used ones include Least Squares (LS), Minimum Mean Squared Error (MMSE) and Maximum A-posteriori probability (MAP) channel estimations. LS is a pilot based channel estimation, which has reasonable performance with low complexity as it doesn't need channel statistics. MMSE has enhanced performance with more complexity as the autocorrelation matrix is exploited [37,38].

Almost all these channel estimation techniques require the inversion of a large matrix which increases the overall complexity of the system; this problem has been focused by many researchers, along with other complexity increasing factors. An adaptive low-complex channel estimation algorithm for MIMO communication was proposed in 2008, which didn't require inactive carriers and made use of symbol decisions and thus reduced number of pilots [15]. It was a combination of two algorithms and their extension to the MIMO channel estimator by using the adaptive synchronization algorithm for OFDM proposed in [9] to multiple transmitters and included sparsing of the channel impulse response from the algorithm proposed in [39]. For M_f adjacent carriers and jth OFDM block, the channel transfer function for each transmitter–receiver pair was assumed as the same, as given by [15]:

$$H^{k+i}_{v,u}(j) = H^k_{v,u}(j), \quad i = 1,\ldots,M_f - 1. \tag{8}$$

And the frequency domain model for channel estimation was given as under, where $\tilde{\mathbf{y}}^k_v(j)$ and $\tilde{\mathbf{n}}^k_v(j)$ have M_f elements each:

$$\tilde{\mathbf{y}}^k_v(j) = \tilde{\mathbf{X}}^k(j)\mathbf{H}^k_v(j) + \tilde{\mathbf{n}}^k_v(j) \tag{9}$$

$$\text{where} \quad \mathbf{H}^k_v(j) = [H^k_{1v}(j),\ldots,H^k_{Ntv}(j)]^T \tag{10}$$

$$\tilde{x}^k(j) = [x^k_1(j)e^{j\theta^1_k(j)},\ldots,x^k_{Nt}(j)e^{j\theta^{Nt}_k(j)}] \tag{11}$$

$$\tilde{\mathbf{X}}^k(j) = \begin{bmatrix} \tilde{x}^k(j) \\ \vdots \\ \tilde{x}^{k+Mf-1}(j) \end{bmatrix}. \tag{12}$$

Compressed sensing (CS) based sparse channel estimation was introduced in UWA MIMO-OFDM communication for the first time in 2009 [40]. The work of B. Li in [29,32] was modified to improve the performance and the channel estimation was included in the iteration loop, which made available the data symbols estimated in previous round as additional pilots for improved estimation accuracy and the LS channel estimator was replaced by a more advanced CS channel estimator already tested in [41,42] that exploited the sparse nature of UWA channels. For the compressed sensing, a large dictionary was defined with $N_T = \beta KTg/T$ entries, where β was the over-sampling factor and the channel was estimated as [40]:

$$\tilde{h} = W\zeta \tag{13}$$

where ζ contained the N_T possible delays corresponding to the dictionary columns but was sparse with a limited number of nonzero entries and W was given by [40]:

$$W = \left[w\left(\frac{T}{\beta K}\right) w\left(\frac{2T}{\beta K}\right) \ldots w\left(T_g\right) \right] \tag{14}$$

where w was the column vector containing $e^{-j2\pi k\frac{\tau p}{T}}$ across subcarriers. The proposed receiver was tested and compared with the previous works including the 'non-iterative receiver' of [28] and 'turbo equalization receiver' of [29] where the proposed iterative receiver outperformed the non-iterative receivers in every applied modulation scheme and number of transmitters [40]. Another channel estimation technique based on CS theory was proposed in [43], which also catered for Doppler shift, using the same dictionary approach for reconstruction of the signals and its effectiveness was proved by testing and comparing the channel estimation performances of basis pursuit de-noising, Dantzig selector and orthogonal matching pursuit. The proposed CS algorithm outperformed the traditional LS method in terms of accuracy [43].

The complexity of channel estimation due to inversion of a large matrix was highlighted by M. Stojanovic in 2009 [44] by proposing two algorithms; first one reduced the complexity by reducing the size of the matrix to be inverted by discarding insignificant channel coefficients, and the second one eliminated the matrix inversion completely. For the first algorithm, LS channel estimation in the impulse response domain was used and a block adaptive method was used for the second one [44]. M. Stojanovic in [45] proposed another adaptive algorithm, using least mean squares (LMS) channel estimator which also didn't require matrix inversion. Here the work done in [9,39] was extended to MIMO systems, where decision-directed, adaptive block processing was used unlike the classical techniques of pilot assisted, block oriented detection, which resulted in improved performance due to reduction in the pilot overhead [45].

Another novel approach to reduce complexity was proposed in 2010 [13], exploiting time and frequency correlation, where the work proposed in [15] was modified by adding a phase prediction method based on adaptive estimation of the Doppler factor from [46] to predict and track non-uniform Doppler shifts along with the reduction in number of pilots. This method also eliminated the matrix inversion by using LMS algorithm. An assumption was made for time correlation that the channel transfer function remained constant between consecutive OFDM blocks so Eq. (8) from [15] remained valid here whereas in the frequency correlation, a sliding window approach was implemented in a recursive manner, so that the full solution didn't need to be computed for every carrier and the LMS recursion is given by [13]:

$$\tilde{\mathbf{H}}_{v}^{k+m}(j) = \tilde{\mathbf{H}}_{v}^{k+m-1}(j) + \Upsilon\, \tilde{\mathbf{X}}^{k}(j) \left[\tilde{y}_{v}^{k}(j) - \tilde{\mathbf{X}}^{k}(j)\tilde{\mathbf{H}}_{v}^{k}(j)\right]' \tag{15}$$

where $m = M_f/2 - 1$ and Υ is the step size.

In order to reduce the computational complexity further, S. Kim [2] in 2012 proposed fully angle-domain frequency-selective sparse channel estimation algorithm, inspired from the work of L. Huang in [47], who proposed an angle-domain channel estimation method for above-water MIMO-OFDM indoor systems. An Orthogonal Matching Pursuit (OMP) algorithm was proposed and the received signal in angle domain was modeled as [2]:

$$\mathbf{r} = \mathbf{D}\mathbf{z} + \mathbf{n} \tag{16}$$

$$\text{where} \quad \mathbf{r} = \left[y_1^a, y_2^a, \ldots, y_{Nr}^a\right]^T \in C^{Ns\,Nr \otimes 1} \tag{17}$$

$\mathbf{n}$ was the AWGN vector in angle domain, superscript a represented the angle domain and $\mathbf{z}$ was given by [2]:

$$\mathbf{z} = \left[\mathbf{H}_{q1}^a(1,:),\ \mathbf{H}_{q2}^a(1,:), \ldots, \mathbf{H}_{qNq}^a(1,:),\ \mathbf{H}_{q1}^a(2,:), \ldots, \mathbf{H}_{qNq}^a(Nr,:)\right]^T \in C^{Nt\,NrNq \otimes 1}. \tag{18}$$

And $\mathbf{D} \in C^{N_s N_r \otimes N_t N_r N_q}$ was the dictionary matrix, where N_q was number of non-zero taps and N_s was number of orthogonal subcarriers. The simulation resulted in more than 50% decrease in the computational complexity as compared to single step OMP algorithm.

In 2012 Z. Sun et al. compared STBC encoded comb pilots with STBC encoded block pilots for channel estimation and found that block pilots outperformed comb pilots in higher SNR with LS linear interpolation [48]. To overcome the effect of slowly time varying feature of the channel on block pilots performance, a complex coded pilot updating method was implemented, where the received OFDM symbols within a specific time slot were used as the new pilots for estimating the channel for the next time slot [48].

Finally in 2014 an innovative differential coherent detection algorithm was proposed which eliminated the use of channel estimation by introducing differential space frequency block codes (SFBCs) with MIMO-OFDM over underwater acoustic channels [49]. After comparison, the differential coherent detection proved superiority over coherent detection based on adaptive channel estimation, where differential SFBC remained operational with up to 2048 carriers (16 kbps), while coherent SFBC failed with more than 512 carriers (10 kbps) because adaptive channel estimation became more difficult across longer blocks (increased number of carriers), resulting failure of coherent detection [49].

4.2. Channel equalization

This is the step after channel estimation and the main aim of channel equalization is to remove the ISI and ICI from the received signal and get the signal into the proper shape just as it was when transmitted. OFDM can achieve low complexity equalization in the frequency domain, which is not possible in time domain equalization due to the large number of taps for highly dispersive underwater acoustic channels. OFDM enables one tap equalization in static multipath channels, however complex channel equalization techniques are required for MIMO-OFDM [50]. Few of the specialized equalization techniques are discussed below.

X. Ma et al. in 2009 proposed a novel approach of blind frequency domain channel equalization based on independent Component Analysis (ICA) technique, which avoided the need for training sequence symbols for higher spectral efficiency [51]. In 2011 the interference cancelation of UWA MIMO-OFDM system in channels having long delay spreads and larger Doppler shifts was highlighted and two equalizers were used simultaneously to achieve the goal [18]; a frequency domain equalizer (FEQ) already designed for radio communications in [52] and a novel time domain equalizer (TEQ). The FEQ of [52] was designed based on the fact that the IBI and ICI affect the received signal in both time and frequency dimensions, therefore, a two dimensional filtering or linear combination was used to compensate these interferences [18]. The time domain equalizer $\mathbf{G}_e^{(u)}[i]$ for uth transmitter, was designed based on maximizing the signal to interference plus noise ratio (SINR) at the output of the FFT demodulator and the transmitted block of uth transmitter is estimated as [18]:

$$\hat{\mathbf{x}}^{(u)}[i] = \boldsymbol{F}\,\mathbf{G}_e^{(u)}[i]\,\mathbf{y}[i] \tag{19}$$

$$\mathrm{SINR}_k^{(u)} = \frac{P_s^{(u,k)}}{P_{\mathrm{ICI}}^{(u,k)} + P_{\mathrm{IBI}_p}^{(u,k)} + P_{\mathrm{IBI}_f}^{(u,k)} + P_{\mathrm{ITI}}^{(u,k)} + P_{\mathrm{noise}}^{(u,k)}} \tag{20}$$

where $\boldsymbol{F}$ denoted unitary fast Fourier transform matrix, $P_s^{(u,k)}$ was signal power, $P_{\mathrm{ICI}}^{(u,k)}$ was ICI power, $P_{\mathrm{IBI}_p}^{(u,k)}$ and $P_{\mathrm{IBI}_f}^{(u,k)}$ denoted IBI powers due to previous and following blocks respectively; $P_{\mathrm{ITI}}^{(u,k)}$ was interference power caused by other transducers and $P_{\mathrm{noise}}^{(u,k)}$ was the noise power.

M. Beheshti et al. in 2012 proposed another time-domain block equalization technique based on MMSE and Zero-Forcing (ZF) criteria to eliminate both IBI and ICI effectively and proposed a novel approach to design two time-domain per-tone equalizers, which minimized bit error rate or mean-square error in each subcarrier [53]. All the previous works in this regard used frequency based per-tone equalization techniques; whereas this was the first time that time-domain per-tone equalization was introduced in UWA MIMO-OFDM [53].

$$\hat{\boldsymbol{x}}[i] = (\boldsymbol{I}_{Nt} \otimes \boldsymbol{F})\, \boldsymbol{G}_{e,\mathrm{MMSE}}[i]\, \boldsymbol{y}[i] \triangleq \boldsymbol{G}_{e,\mathrm{MMSE}}[i]\, \boldsymbol{y}[i]\,. \tag{21}$$

Eq. (23) showed that the transmitted QAM symbol on each subcarrier could be estimated using a linear combination of the received data samples of all receive transducers, where $\boldsymbol{I}$ is the Identity matrix and $\boldsymbol{G}_{e,\mathrm{MMSE}}$ is the time domain MMSE equalizer, which was used as a basic fact to propose two time-domain-per-tone equalization [53].

Three different equalization schemes were compared for different numbers of transmitters and receivers in 2013 [54]: ZF detector, MMSE equalizer and MMSE-SINR-OSIC (signal-interference-plus-noise-ratio, ordered successive inference cancellation), where in the third method, MMSE was used as signal estimator and SINR-OSIC for OSIC detection and error-free performance was achieved using 2048-QPSK packets at a data rate of 21 kb/s and MMSE-SINR-OSIC outperformed the other two methods [54]. A novel algorithm for channel equalization was proposed by J. Hao et al. in 2015 [55], who extended the SISO design in [56] and introduced Time Domain Synchronous (TDS) as a new OFDM transmission scheme based on turbo equalization and iterative channel re-estimation for underwater acoustic communication, where time-domain sequences were used as the guard intervals and as the training sequences to enhance the overall data efficiency instead of the conventional ZP and CP OFDM, where padded zeroes and cyclic prefix were used as guard interval. The proposed system was compared with the conventional techniques and the MIMO TDS-OFDM scheme achieved better performance with low complexity and high data efficiency [55].

J. Han et al. in 2016 did the most recent and novel work in this area by mitigating the ICI over time-varying underwater acoustic channels by introducing and implementing a newly emerging partial FFT technique [57]. An adaptive algorithm was proposed with zero a-priory channel information assumption, which jointly performed sliding-window channel estimation, weight updating and data detection; and thus partial FFT combining was applied across subcarriers iteratively by dividing the OFDM symbol duration into l non-overlapping intervals and performing a Fourier transform on each windowed segment, where the output of the lth segment on the kth subcarrier at receiver v was given by [57]:

$$y_v^k(l) = \sqrt{\frac{1}{T}} \int_{\frac{(l-1)T}{L}}^{\frac{lT}{L}} y_v(t)\, e^{-j2\pi(k-1)\Delta f t}\, dt. \tag{22}$$

The performance of this algorithm has been tested through simulations, and the results and BER curves proved that this method performed far better than the other techniques in practice over time-varying UWA channels [57].

4.3. Detection

Detection basically means to detect the information signal in the raw and noisy data being received. MIMO-OFDM detectors/receivers contain a combination of different algorithms which performs all the tasks like detection, estimation, equalization, decoding etc. The following papers focused on the detection schemes and explained different types of detectors.

Turbo-detection techniques are important due to their potential to approach the matched filter bound at moderate frequency in UWA communication, quite limited work has been done on implementing turbo detection for MIMO OFDM including the work done by B. Li in [32]. Another turbo-detection technique for MIMO-OFDM was developed by J. Tao and R. Zheng [58], where the linear symbol estimation benefited from a hybrid soft interference cancelation and a reliability based detection ordering enabled by the a priori information at the equalizer. J. Tao et al. [59] introduced another detector using Zero Padded oversampled-orthogonal frequency division multiplexing (OOFDM) technique, where oversampling and pilot-based channel estimation were performed in time domain whereas symbol detection and signal processing in frequency domain while ZP was selected due to its less transmission power requirement. The beauty of this detector was that it could be directly applied to the received OFDM signals without any changes in transmitting end. An oversampling factor β was introduced, which was an integer larger than 1, which helped in achieving extra diversity gain by sampling the received signal at a rate higher than symbol rate and it was found that the detection performance increased with the oversampling factor [59].

The issue of different Doppler scaling factor by each transmitter–receiver pair was highlighted in [21,60] and proposed a front-end receiver structure that utilized multiple re-sampling branches, one for each transmitter, and resulted in capturing complete information available in the channel and thus improved the efficiency and performance as compared to the systems already in practice using single re-sampling branch. The received signal for different Doppler distortion for a total of N_p paths was given by [21]:

$$y_v(t) = \mathrm{Re}\left\{ \sum_{u=0}^{Nt} \sum_{k=0}^{K-1} \sum_{p=0}^{N_{p-1}} s_u[k]\, h(v,u,p)\, e^{j2\pi f k (t + au(t) - \tau(v,u,p))} \times R(t + au(t) - \tau(v,u,p)) \right\} + \widetilde{n}_v(t) \tag{23}$$

where $R(t)$ is the rectangular pulse of duration $T + T_g$. Three different types of detectors: Maximum Likelihood (ML) detection, linear detection based on LS or MMSE optimization criterion, and nonlinear detection based on interference cancellation (IC) were used after the re-sampling and FFT operations [21,60].

J. Huang et al. [61] introduced a novel approach of treating ICI explicitly, together with the co-channel interference (CCI) due to parallel transmissions in MIMO-OFDM as all the existing receiver designs including the works in [28,32,45] treated ICI as an additive noise. The observation $o_v[m]$ of mth sub-carrier of the vth receiver, with D direct neighbors and equivalent noise $nn_v[m]$ consisting of both residual ICI/CCI and ambient noise was expressed as [61]:

$$o_v[m] = \sum_{u=1}^{N_t} \sum_{k=m-D}^{k=m+D} H_{v,u}[m,k] s_u[k] + nn_v[m]. \tag{24}$$

The proposed receiver involved CS based sparse channel estimation, noise variance estimation, soft-input soft-output MMSE/Markov Chain Monte Carlo (MCMC) detector for ICI/CCI equalization and LDPC decoding scheme [27,62]. The problem of different Doppler shifts and different number of data streams for different users in a multi-user MIMO system was also targeted by J. Huang et al. in 2013 and two iterative receivers were proposed to coup this issue in MIMO-OFDM systems: multiuser detection (MUD) based receivers and single-user detection (SUD) based receivers [22]. A frequency domain oversampling front end on each receive element was adopted in MUD based receiver, then joint channel estimation and multiuser data detection were performed iteratively, whereas conventional single user processing modules were adopted in the SUD-based receiver with the addition of an important step of multiuser-interference (MUI) cancellation [22].

UWA MIMO-OFDM was extended to multimedia applications in 2013 and a receiver was designed to meet the Quality of Service (QoS) requirements keeping in view the Doppler compensation due to network nodes mobility [63]. The design consisted of three nodes at different depths; a source node, destination note and a relay node, which worked as an amplify and forward node and the simulation results proved that the performance capacity got better with the increase in number of transmitters [63,64]. In the same year C.F. Lin et al. [65] also successfully completed multimedia communication (image, sound and sensor data), using MIMO-OFDM in underwater environment. They used direct mapping, space–time block code, adaptive modulation and Double Window Detection algorithm for detection of Signal to Noise ratios (SNRs) of sensor data, image and audio packets. The proposed design was successfully tested in real time and much clearer image, audio and sensor data were received with higher data transmission rates with relatively low bit error rates and minimal power requirements [65].

4.4. Channel coding

Channel coding simply means to add some redundancy in the useful bits in order to protect the data in noisy channel. Dedicated studies for UWA communication channel coding are quite limited and often well studied coding schemes from existing literature were picked up, e.g. Trellis Coded Modulation (TCM), convolutional codes, Reed Solomon (RS) codes, turbo codes, Space time trellis codes and low density parity check codes. Each UWA channel needs a special coded modulation scheme depending on channel characteristics, because a scheme designed for a specific channel may not perform well in another channel due to the different channel statistics. Non-binary LDPC coding is one of the widely used coding technique being preferred for MIMO-OFDM, as it already outperformed many coding schemes in complexity and performance in case of radio communications as well as SISO-OFDM communication. The LDPC decoding is done in two phases; the first phase includes the computation of all messages from the variable to the check nodes using log-likelihood ratios (LLRs), while in second phase all messages from the check to the variable nodes are computed [66,67].

Two coded modulation schemes were implemented and compared in [50]; first scheme combined trellis coded modulation (TCM) based on an 8-phase-shift keying (8-PSK) signal set and symbol interleaving, while the second scheme was based on bit-interleaved coded modulation (BICM), which included a convolutional encoder, a bit interleaver, and a 16-quadrature-amplitude-modulation (16-QAM) signal set. It was found that BICM scheme performed better when the channel exhibits a low diversity order (limited special diversity), because of the higher Hamming distance in BICM, which is a key parameter for achieving robust performance in fading channels. While the TCM scheme was a better choice when the channel demonstrated a high diversity order (sufficient spatial diversity), because of the higher coding gain of TCM, which is the key parameter for achieving better performance in the AWGN channel [50]. In 2014 Nelson et al. proved 1/2 code rate turbo code, as an effective channel encoder and employed iterative decoding algorithm at the receiver side to alleviate the effects of ambient noise and acoustic interference in MIMO-OFDM UWA communication system [68].

5. Conclusion and future work

This paper gives an overview of almost all the previous works in the field of UWA MIMO-OFDM communication. Different researchers have focused on different issues and it can be concluded that an efficient single communication design with specific algorithms that could be used in all types of underwater channels, has been elusive. The transmission design deeply depends on the channel conditions like different schemes should be used in shallow water than deep water and different algorithms need to be exploited for rough and calm channels, multipath rich channels and channels with severe Doppler Effect. Even the number of sub-carriers should be large to cater for larger delay spreads in OFDM but should be small for systems having larger Doppler spread. The type of channel equalization also depends on other parameters like channel estimation and coding. Coding depends on the communication types (e.g. audio or command communication systems) and the accuracy and reliability required in the data transmission.

For the simple MIMO-OFDM communication systems, null carriers and pilot carriers could be inserted for Doppler shift estimation and channel estimation respectively. Among Channel estimation techniques, LS estimation has the least complexity and MMSE has high efficiency with increased complexity. The complexity of channel estimation was first drastically reduced by the techniques avoiding the inversion of matrix during channel estimation, then with the introduction of differential space frequency block codes (SFBCs), even the need for channel estimation was eliminated [49]. The TEQ techniques like time-domain block equalization, Time-Domain-per-tone-equalization and TDS with turbo equalization relatively performed better than the other conventional equalization schemes. The performance of treating ICI explicitly, together with the CCI, is far better than treating ICI as an additive noise.

MIMO-OFDM in UWA communication is relatively new field and there is a lot of room for more research as no algorithm is labeled as the perfect one, all techniques have their benefits with somewhat compromise on complexity, effectiveness or efficiency. A low complex, highly efficient channel estimation scheme is still hard to find. We need to exploit the characteristics of UWA channel (e.g., sparsity of channels, channel coherence across blocks) to improve the performance of channel estimation in MIMO-OFDM system. A channel coding scheme with low complexity level and proper mitigation of ICI and ISI need attention of the researchers. More number of transmitters needs to be tested and their response needs to be analyzed, as mostly researchers have tested up to 4 transmitters so far. Quite little work has been done on the elimination of PAPR in UWA MIMO-OFDM, though many techniques have been proposed for SISO case.

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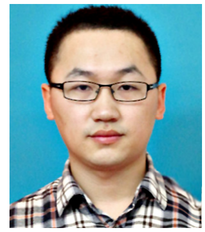

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