Research Journal of Applied Sciences, Engineering and Technology 5(3): 778-789, 2013
DOI:10.19026/rjaset.5.5022
ISSN: 2040-7459; E-ISSN: 2040-7467

Submitted: June 07, 2012 Accepted: July 18, 2012 Published: January 21, 2013

Research Article

A Survey of Underwater Acoustic Communication and Networking Techniques

Khan Rehan and Gang Qiao
Science and Technology on Underwater Acoustic Laboratory, Harbin Engineering University, Harbin 150001, China

Abstract: The study presents the details of recent developments and innovations in the field of Underwater Acoustic Communication (UWAC) and networking that may be act as a requisite platform for the individuals who want to involve in the research of this emerging field. Ocean exploration/monitoring applications make design of robust UWAC and networking systems more demanding for recent researchers. The main objective of these studies is to establish a standard, low complex and real-time acoustic network having the capabilities to handle the extremely complex and continuously time varying nature of sea. During last decade, major contribution in this field has been carried out; many efficient methodologies and algorithms have also been proposed. In terms of physical layer, coherent MIMO-OFDM based communication is considered as feasible solution for the band limited/frequency selective underwater channel with more spectral efficiency, high data rates and reliable links. Considering the implications of complicated aquatic channel characteristics (extremely limited bandwidth, noise, Doppler spread, multipath, complex propagation delay), many researchers are also focusing for the developments of effective MAC protocols in terms of capacity and reduced consumption of power. Routing strategies that establish efficient data delivery paths in underwater environment is another demanding requirement. Designing of Transport layer protocol for fluctuated aquatic environment is an open research area.

Keywords: Channel estimation, MAC protocols, Matching Pursuit (MP), multipath spread, Multiple Input Multiple Output (MIMO), non-uniform Carrier Frequency Offset (CFO), Orthogonal Frequency Division Multiplexing (OFDM), routing strategies, Underwater Acoustic Communication (UWAC), Underwater Acoustic Network (UAN)

INTRODUCTION

Underwater wireless information exchange and networking are one of the demanding areas of research and development for numerous applications in terms of ocean-monitoring systems. These systems may include the exploration of marine life, image broadcasting from remote sites, environmental monitoring, seismic alerts, collection of scientific data both, pollution control, object detection in sea floor, control of AUVs and other security/military based applications. Domingo (2011) has explained the idealized models of 2D sensors, 3D sensors and 3D sensors with AUVs for the application of underwater networking. Model for 3D sensors with AUVs is shown in Fig. 1. Recently, many studies and analyzes in this field have been carried out to make more control on underwater wireless information exchange. In this study, we are presenting a survey about the recent advancements, specifically during last decade, in the field of UWAC and networking. Considering the extremely complex behavior of ocean, various methodologies have been suggested for an efficient underwater acoustic communication. As, for the great multipath effect with strong noisy environment of marine channels, the most promising multicarrier modulation technique (i.e., OFDM) are being effectively utilized in the recent researches. However, the dominant non uniform carrier frequency offset due to motion induced Doppler distortion in OFDM signals had to be compensated. Therefore, many researchers, focused on the exploration to investigate the methodology for the reliable detection of OFDM signal received from Doppler distorted and time varying channels.

One of the major tasks in the receiver design which is extremely challenging in the UWA communication is channel estimation. In recent years, lots of researches on channel estimation have been carried out for the subsequent low complex equalization procedure in frequency-domain OFDM systems. Some techniques are adaptive joint iterative estimations and decoding based methods while some based entirely on special training or pilot symbols. The objective of these techniques is to get high quality detections and minimization of BER. Sparsing of channel (BP, OMP) by estimating in a time domain has also been proven to be an effective method for better performance of the

Corresponding Author: Khan Rehan, Science and Technology on Underwater Acoustic Laboratory, Harbin Engineering University, Harbin 150001, China

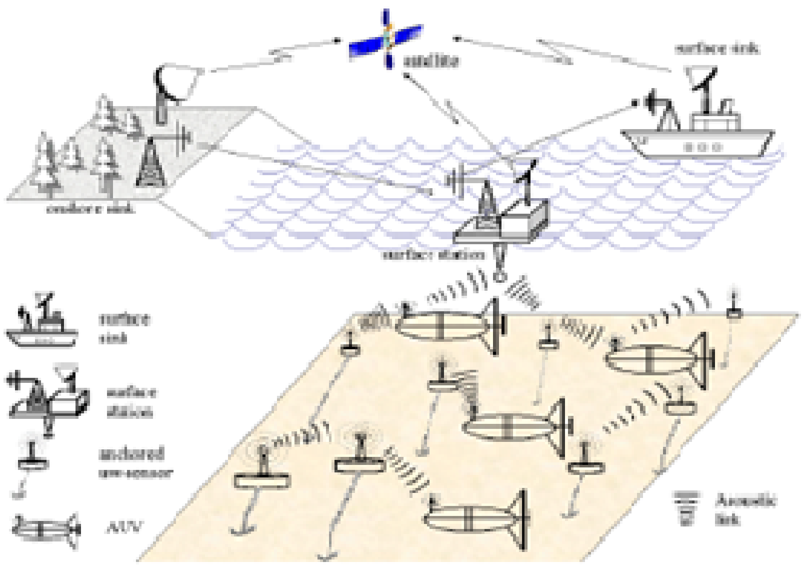

Fig. 1: 3D sensors model with AUVs (UAN)

system, i.e., higher received signal's SNR. Moreover, study on phase noise (i.e., phase shift between carrier and local oscillator due to channel complexities) suppression techniques are also being focused in the current researches for precise detection and decoding of the transmit information. Another problem induced by OFDM system is higher values of Peak and Average voltage Ratio (PAR), many coding techniques, proper mapping procedures, inserting interleaves have been studied to reduce the PAR and recent DFT spread method is found to be an effective method, specifically for minimizing PAR.

Since the underwater channel is extremely band-limited and frequency selective, the requirement of communication with maximum possible utilization of bandwidth and higher data rates are very essential. Consequently, like RF communication, the concept of Multiple-Input Multiple-Out (MIMO) OFDM system has been originated for the underwater acoustic communication for increasing the channel capacity and more spectral efficiency. Thus in terms of physical layer, the proper and efficient operation of underwater coherent OFDM system demands the spatial multiplexing, estimation of CFO and it compensation, phase noise suppression, adequate reduction in PAR, channel state information and low complex equalization. In addition to coherent OFDM method, feasibility of normal mode decomposition as a preprocessing step for underwater acoustic communication has also been investigated. The robust design of physical layer is acted as an important platform for the higher layers and extensive improvements on this layer will provide higher data rate and low BERs for underwater communication networks. One of the fundamental constituents of any communication networks is the capacity of a link. Its knowledge is very essential, especially in design of higher layers for network planning and resources management.

For underwater acoustic networks, appropriate design of Medium Access Control (MAC) layer is very critical. Over very complicated environment of underwater acoustic channel, intelligent design of MAC layer can offer the optimize scheduling for the access of physical layer and accordingly, the allocation of available resources among the nodes of Underwater Acoustic Network (UAN). The usefulness and effectiveness of both distributed and centralized MAC with contention-based or non-contention based design for UAN are being evaluated in the current studies. The main issues of underwater acoustic channel include the extremely limited bandwidth, multipath effect, propagation delay and dynamic nature of sea that can deteriorate the performance of the fast data-rate schemes i.e., OFDM communication system. In this context, a flexible MAC design having avoidable overhead, fading-less feature, simple concurrent transmissions, optimized energy utilization and perfect modulation technique will be the preferable choice.

In communication, network layer determines the path from a source node to the destination, when a multi-hop is needed. The same routing strategies and their significances as used in terrestrial communications networks are also very much convincing for the underwater case. However, due to the extraordinary complex and frequency limited behavior of sea many of the standards routing techniques like proactive and reactive packet switched are not being preferably utilized. Transport layer is an important part of an OSI layer model; it ensures that error-free, in sequence, no redundant message delivery through segmentation, acknowledgement, traffic control of message and session multiplexing. Design of a transport layer scheme appropriate for harsh underwater environment is very challenging task and currently open research area. In order to make an efficient design platform for UAN, cross layer design approach has also been considered in the recent studies and regarded as a novel approach for underwater communication techniques and networking.

The prime objective of this study is to provide details of design challenges and to aware the feasibility of recently developed techniques for the development of UWAC and network systems. This literature will be very beneficial for the researchers who are involved and intend to involve in this appealing field of UWAC and networking.

THE DESIGN OF PHYSICAL LAYER

During last decade, many researchers focused on the studies and development of the appropriate scheme for underwater acoustic communications. Provision of a standard communication model that could be utilized as a benchmark (like in RF communication) in any pelagic environment may be considered as delusion. Nevertheless, many of the researchers presented the outstanding approaches and deliberated for various schemes of physical layer comprise of robust data packet's structure against extremely complex oceanic conditions. Out of them, one of the most intelligent approaches was the design of UWAC system based on coherent multicarrier modulation structure (i.e., OFDM). The main requirement to use this technique is the maximum possible minimization of effects from Multipath spread and inter-symbolic Interference, which is more dominant in the oceanic communication. The OFDM based systems was initially developed for RF ground based communication systems and are being utilized for recent broadband communications and advance 4G systems. During last ten years, studies and analyzes on various aspects of underwater acoustic communication based on OFDM have been carried out and it is found to be best suited for underwater acoustic communication system and basis for networking. For more spectral efficiency and high data rates, spatial multiplexing based OFDM has also been studied, so in terms of physical layer; coherent MIMO-OFDM systems have considered ideal choice for the extremely band limited and dynamic nature of underwater channels. The developments and implications of underwater coherent OFDM system as briefly explained in Khan *et al*. (2011) are described in the next subsections.

Protection from strong multipath effect: Underwater acoustic channel has very strong multipath effect due to the higher probability of reflections from wavy sea surface, uneven sea bottom and other obstacles. Therefore, the transmitted signal reflected several times before reaching to the receiver such that many delayed replicas of the same signal are also received that cause destruction of original signal in terms of Inter-Symbolic Interference (ISI). Longer, the channel time delay will cause more ISI and in the underwater channel, this delay is much more dominant than ground based channel. In order to avoid this destruction of the signal, multicarrier schemes were analyzed for underwater acoustic communication. The multicarrier modulation divides the channel time delay by the number of sub-carrier to decrease the impact of ISI. In OFDM, more feasible multicarrier scheme, by using the additional spacing more than the maximum channel delay can completely diminish the destruction effects of multipath spread. Considering this idea of extra space with the repetition of some part of message carriers within sub-carriers as a called Cyclic Prefix (CP) were rightly explained in Kang and Litis (2008), Chitre *et al*. (2005) and Nasri *et al.* (2009). The concept of CP is very promising and effective to minimize the effect of ISI by converting linear convolution problem to a circular convolution problem. So, that ISI can be handled through low complex equalization. However, it requires more power, which is unsuitable for underwater modems. Consequently, padding of zero bits instead of repetition of the message signal was explained and effectively used in Parrish *et al*. (2008), Li *et al*. (2008) and Wang *et al*. (2010). Both ZP and CP schemes offer the low complexity equalization in the frequency domain. As shown in Fig. 2, we have to calculate interval length in such a way that it should not be so small to be ineffective to reduce the major contribution of ISI and similarly, it should not be too long to be the basis of low data rate. Thus proper design of ZP/CP based OFDM not only protects acoustic information from the strong multipath effects but also offer high-rate communication and low complex equalization and detection procedures.

Minimization of doppler shift effects: OFDM based underwater communication system is very sensitive to the frequency offset due to its wide-band nature; little shift may cause overlapping of sub-carriers such as that

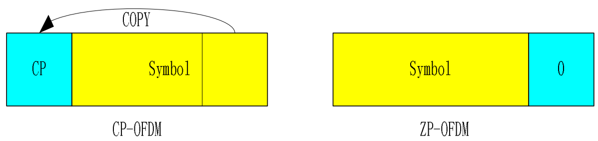

Fig. 2: CP scheme (left) and ZP scheme (right)

entire signal can get completely distorted. Another reason is the slower speed of sound in water as compared to RF communication that causes oceanic dynamics more dominant and that may cause Doppler shifting in the signal in the form of sub-carriers overlapping. This type of overlapping is termed as Inter-Carrier Interference (ICI) that is the major problem in OFDM based underwater communication systems; it can damage the orthogonality between the sub-carriers. ICI may also be occurred due to mismatching between the local oscillators frequencies. The Doppler shift in terms of amplitude and phase occur due to the relative motion between transmitter and receiver. These distortions are non-uniform and extremely complex due to the dynamic nature of sea and therefore, appropriate methods to overcome this sensitive problem are very essential. It is noteworthy that the effect of Doppler shift will be lessened if sub-carriers spacing is more than the maximum possible frequency deviation and may provide better results. During last ten years various algorithms and techniques have been proposed for the minimization of non-uniform Doppler shift effects from the OFDM based UWAC systems. These proposed methods are based on two schemes: one based on null carriers for the phase synchronization such that it can handle fast oceanic variations and second is an adaptive approach that considers phase coherence between successive OFDM blocks.

Null carrier's scheme has been applied in Li *et al.* (2008) for Doppler scale estimation and its subsequent compensation through two-step procedure. Initially, re-sampling is used to convert the wide-band problem to narrow-band problem for non-uniform Doppler minimization and then residual Doppler is combated through high resolution search procedure. This two-step mitigation problem is highly inspiring and provided low BERs and high date-rate even in very fast relative motion between transmitter and receiver, however, it offers more overhead. The same scheme with the addition of frequency domain oversampling step within the specified configuration gap between the pilot symbols and the data symbols has been evaluated in Wang *et al.* (2010). The simulation and experimental results explain the significance of this scheme that is it offers more robustness against larger Doppler spreads. In Thottappilly (2011), author proposed new time warp based correction technique and performed experiments in air, the high-quality results explain the robustness of this scheme even in much faster and more varied kinds of motion. The importance of compensation of non-uniform Doppler shift has been highlighted in Stojanovic (2008), which is based on the simple phase tracking model. In Stojanovic (2006), an adaptive phase synchronization method along with sparse estimation of channel is described to mitigate the non-uniform Doppler shift. The experimental results are very promising and have smaller overhead by eliminating null's carriers and reducing the number of pilot carriers. The adaptive schemes are also utilized in Stojanovic (2009) and Carrasosa and Stojanovic (2010) for MIMO configuration based on decision directed operation. These algorithms provide low latency and good error performance. In Tianyu *et al.* (2010), another adaptive scheme based on second order phase locked loop has been illustrated that relies on feedback of decoding symbols instead of decisions. The experimental results showed high level of accuracy in cost of some computational overhead. Two novel schemes: one based on ICI coefficient estimation with close loop tracking algorithm and other is adaptive mitigation technique for ICI without the knowledge of ICI coefficient are demonstrated in Tu *et al*. (2009). Both schemes showed convincing improvements, especially in high SNRs. However, the latter one is more robust against strong Doppler shifts.

Reduction in PAR and SNR: In OFDM based UWAC systems, one of the major problems is the higher peak-to-average power ratio due to the superposition of signals of all sub-carriers. The constructive accumulation of these signals makes peak power much higher than the average power. Thus, more power requires for power amplifier and these random peaks lead to make the low efficiency system. In order to avoid this effect, the OFDM system having a more expensive power amplifier that can be capable to give high linearity and a wide dynamic range is required. Many PAR reduction techniques have been proposed based on pre-coding, clipping method, selective mapping method, proper insertion of interleaves, etc.; however, in each method, side information along with actual information is required that cause transmission rate slower. In Han and Lee (2004), the author described a novel approach based on the signal set expansion that reduces PAR effectively without transmitting any extra information with transmitting signal, but it offers more complexities and overheads with the level of reduction.

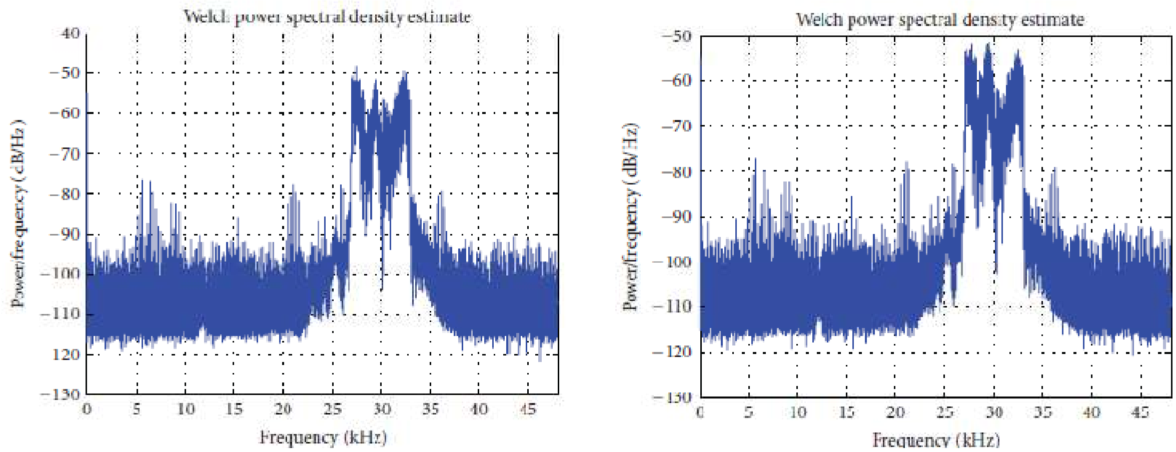

Fig. 3: Power spectral density of proposed DFT spread system (left) and conventional OFDM system (right)

Another method in Zhang *et al*. (2010) that utilizes additional DFT operation in OFDM system considerably reduces the PAR and provides the excellent results. The outstanding simulation and experimental results prove the applicability of this method in complex underwater environments in the cost of little overhead. Figure 3 shows the effect of DFT spread OFDM technique.

An accurate SNR estimation for any wireless communication system is an essential design step for the proper channel estimation, adaptive modulation and coding techniques, soft decoding algorithms, etc. In this connection, the requirement of low complexity and an exact method for the UWAC SNR estimation is very important and challenging. In Weijie *et al*. (2011), highly efficient method based on single pilot symbol is applied to DFT spread OFDM system that can estimate SNR accurately in very complex and extremely frequency selective underwater channel. The algorithm estimates the SNR by measuring noise variance and second moment calculations of the received signal. Thus, it can be robust against oceanic complexities if implemented with DFT spread OFDM systems.

Efficient channel estimation and equalization: Initially, adaptive channel estimation schemes as mentioned in Arshad *et al.* (2003) were mainly proposed for RF communications. In Stojanovic (2008), adaptive channel estimation and phase tracking method relies on low complex post FFT processing and MMSE combining has been described. The significance of this algorithm was shown to be very convincing for slow moving underwater channels in such a way that only one parameter called as Doppler rate can track phases of all carriers. Satisfactory results with the minimum inter-carrier spacing from 1024 sub-carriers per block were achieved from the experiment. The concept of sparse underwater channel estimation has been introduced in Stojanovic (2008) by simply magnitude truncation of time domain channel coefficients. Thus, noise factor can be minimized and resulting yields would be the high SNRs and low computational overhead. The proposed method based on coupling of sparse estimation with adaptive synchronization of ZP OFDM signal such that it can give improved performance with larger bandwidth efficiency by offering higher number of sub-carriers. Orthogonal Matching Pursuit algorithm (OMP) along with sparse channel coefficients has been proposed for channel estimation in Kang and Litis (2008). This pilot tone based method first calculates the maximum delay and significant channel taps for sparsing and then after CFO estimation of CP OFDM, matching pursuit is applied for accurate channel estimation. OMP algorithm re-computes the taps using the least square estimation to maintain the orthogonality and provide the minimum residual error. The experimental and simulation results with LDPC coding and without coding show the finest performance of this scheme over fast varying channel that uses simpler matrix inversion. Moreover, we have also made the comparison between LS and MP channel estimation in MATLAB. We considered the model of sparse channel with non-uniform Doppler shift in our simulation. Results are shown in Fig. 4. In Tu *et al.* (2009), significance of iterative procedure for sparse channel estimation has been highlighted. The algorithm is a hybrid design that uses the sparse channel estimation based on Basis Pursuit (BP) scheme, MIMO detection using MMSE equalization with successive inference cancellation and non-binary LDPC decoding schemes. Various feedbacks in terms of full-soft, full-hard and threshold controller hard are applied to different constellations for the viability of iterative channel estimation and decoding. The detailed

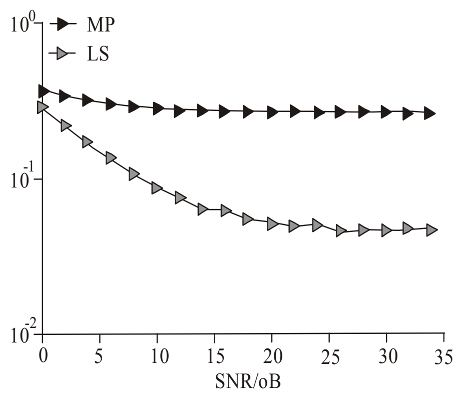

Fig. 4: LS vs MP channel estimation schemes

experimental and simulation's results show that iterative procedure suits very much for MIMO OFDM UWAC as compared to non-iterative procedures. Sparse channel estimation and data detection using MMSE equalization has been also described in Wang *et al*. (2010) with an added over-sampling feature. The algorithm is well suited for data detection even in higher Doppler spreads.

The comparison between three well known schemes of BP has been made in Huang *et al.* (2010a) to find the most effective sparse channel estimation for complex underwater environments. The evaluation has been made in terms of BER and computational latency for both single and multiple transmitters ZP OFDM systems. It has been found that BER performances of all three schemes are almost same. However, the computational latency of SpaRSA and YALL1 are better than l1_ls and can be suited for underwater real-time applications. Moreover, OMP found to have worst BER values as compared to all three BP schemes. The algorithm that uses the combination of joint synchronization-equalization and joint iterative equalization and decoding has been described in Tianyu *et al*. (2010). This technique utilizes decoded symbols for feedback to the Decision Feedback Equalizer (DFE) for mitigating and compensating the effects induced by underwater channel. The results are more accurate as it uses decoded symbols instead of decisions for iterative feedbacks; however, it offers a little bit more computational overhead than the conventional DFE schemes.

Spatial multiplexing through MIMO design: Underwater acoustic channel is extremely a band limited and frequency selective in nature. Numerous applications necessitate the proper design that can support higher data rates; however, due to the increasing absorption effect with frequency limits the operational band of UWAC systems. Thus, there is a need to develop some techniques that can efficiently utilize limited functional bandwidth and can give maximum possible data rates. In this connection, a spatial multiplexing technique is considered to be a promising candidate who can form MIMO system by utilizing multiple transmitters and receivers. For the difficult oceanic conditions, the high spectral communication with low complex solution can be implemented through MIMO-OFDM systems. Recently, many researchers have focused on the development of various algorithms for MIMO-OFDM UWAC. The main task of all studies is to make real-time UWAC system that can utilize maximum capacity of underwater channel, provides maximum possible date rates and suitable for higher layer design. Initially, an experimental analysis based on MIMO-OFDM has been conducted by Palou and Stojanovic (2009) for identifying the different aspects of design and limits of ocean on the performance of MIMO system. Design's aspects are considered as the limit on the number of sub-carriers and the maximum number of transmitters that can be feasible in the complicated oceanic environment. An experimental analysis shows that underwater channel may cause the interference between the multiplexed data streams with increasing number of transmitter and choose the appropriate design with two transmitters. ICI compensation along with sparse channel estimation is also included in the design to make possible to use more sub-carriers for MIMO-OFDM system. The analysis was fruitful, but it offers communication design with a limited number of transmitters which in conditions fails the actual concept of spatial multiplexing.

An adaptive algorithm in terms of decision directed operation is demonstrated in Stojanovic (2009) for MIMO system configuration. The goals of this method are to mitigate the effect of long channel spread, which is more dominant in the multiplexed aquatic channel, maximize the bandwidth efficiency (i.e., number of transmitter and number of sub-carriers) and lowering the computational complexities. Author has clarified for MIMO design that choice of the number of transmitters and sub-carriers should be selected in such a way that maximum bandwidth efficiency can be achieved with pre-specified error performance. MIMO-OFDM design algorithms have also been proposed by Li *et al*. (2009) and Huang *et al*. (2010b) to enhance the spectral efficiency over an underwater communication link. Experiments have been conducted for different constellations and different number of transmitters to obtain the most doable pattern for MIMO design. Iterative hybrid detection and LDPC decoding are the part of these designs while phase synchronization and channel estimation are carried out separately through null sub-carriers and pilot sub-carriers. Experimental results show that the high spectral efficiency can be obtained with higher-order constellations and more transmitters in cost of performance loss. In Tao (2010), a new adaptive MIMO equalization scheme has been proposed for single carrier system. In this method interference cancellation and Doppler tracking is also performed separately in such a manner that previously detected symbols can be used for MIMO channel tracking. Moreover, MIMO turbo BDFE for single carrier system has also been proposed and gives very promising experimental results. Detailed experimental analysis based on the adaptive algorithms for MIMO-OFDM is described by Carrasosa and Stojanovic (2010) that relies on time and frequency correlations. In this algorithm, main consideration was the reduction of complexities caused by multiple transmitters. Suboptimal results are achieved by exploiting time and frequency search for channel estimation. Requisite number of sub-carriers and transmitters are optimized with the size of windows both in the frequency-time (sliding) domain for different experimental settings. In addition, phase tracking and sparsing of channel have also been considered in the design for good results and low computational overhead. This experimental study is very promising for future research and provides the convincing demand of MIMO-OFDM UWAC for physical layer design.

DESIGN OF MAC LAYER

In Akyildiz *et al*. (2006), the detailed requirement and usefulness of underwater acoustic communication networking have been highlighted. Various aspects of network design and challenges for the harsh aquatic environments are comprehensively briefed. Regarding the MAC layer design, CSMA and CDMA based protocol and their suitability for the UAN is also explained. The main deficiencies of slotted FAMA as low system throughput, PCAP as lacking performance of heterogeneous medium and distributed energy-efficient MAC as low bandwidth efficiencies are covered in the CSMA protocols. The important features of the spread spectrum based CDMA protocols namely DSSS and FHSS with and without multicarrier transmission are discussed for high rate and ISI-free communication links. CDMA based energy-efficient schemes and related issues in terms of low complexity encoder/decoders, power saving distributed design and data packet length for maximum utilization of bandwidth are also highlighted. The c and distributed topologies for static, dynamic contention free and contention based MAC protocols are reviewed by Chitre *et al*. (2008). It has been explained that adaptive and power saving schemes are main aspects for maximizing the channel capacity and efficiency. Merits relevant to ranging channel estimation and demerits due to high latency of RTS/CTS handshaking in dynamic protocols are discussed. Underwater acoustic cellular network considers there an extension of centralized topology. In Syed *et al*. (2008), a new MAC protocol strategy that relies on detection of collision, contenders and power saving through space-time uncertainty and low power wake-up receivers is proposed. Another MAC protocol "Receiver-Initiated Reservation-Based" for UAN is proposed by Chirdchoo *et al*. (2008) that use long packet schemes and cross talk from a neighbor at the receiver to decrease the overhead cause due to coordination procedure. In (Li *et al*., 2009), many aspects of MAC layer protocols have been discussed; author explained that FDMA is not a suitable candidate for UAN as underwater communication offers extremely limited operational bandwidth. Due to long time delay factor, TDMA is also considered here to be unsuitable for UAN. Author mainly focused on the spread spectrum schemes of CDMA due to higher efficiency, better throughput, robustness against

Table 1: Recently analyzed Mac protocols for UAN

Mac protocols for UAN	
Name of protocol	Characteristics
Centralized TDMA	Energy efficient and adaptively controlled
Less-throughput TDMA	Based on centralized node control configuration
TDMA/CDMA	Increament in data rate by reducing length of TDMA slot Chances of more interference in the adjacent nodes
CDMA/MACA and MACAW	Slow procesing time Extremely high throughput Good performance for receiving packets
TDMA-CDMA with MACA (RTS/CTS)	Suited for stationary and static nodes, but not for high motility nodes
CDMA	Near far problem Well suited in shallow water
CSMA/CD	Not suitable for single channel packet radio network Construction complexities for full duplex wireless underwater CSMA/CD system
Slotted FAMA	Time slots limit the delay in propagation
UWAN-MAC	Adaptation of the sleeping MAC for energy savings in delayed aquatic sensors networks
DACAP (Distance Aware Collision Avoidance Protocol)	Scalable for number of nodes and coverage area of network

multipath effects, flexibility to switch from one signal to another signal, coherently combining through rake receiver and concurrent transmission. However, efficient power control schemes should also be adopted in the multi-user CDMA to avoid the great interference problems in UAN. The effective implementation of CDMA in UAN is current research area. Effectiveness and characteristics of various MAC's protocol analyzed for UAN were summarized by Nasri *et al.* (2009), which are appended in Table 1.

In Zhou *et al*. (2010), OFDM based MAC protocol called TDM with FDM over OFDM MAC (TFO-MAC) protocol is proposed to get full gain from newly developed OFDM modems. The proposed protocol considers only uplink traffic, one hop UAN that optimally utilizes the transmission power, modulation modes, dynamic channel assignment and available bandwidth. Bandwidth is divided into sub-bands through FDM; time is divided into slots and then OFDM is used for data transmission such that one OFDM block is transmitted in a slot that based on the group of super frames. Greedy algorithm is next applied for the dynamic assignment of channel and subsequent maximization of power and modulation mode. The simulation's results in terms of scaled network, variations in the number of channel and required traffics are found to be very useful for real-time implementation and future work.

DESIGN OF NETWORK LAYER

Research and analyzes regarding the design of suitable routing strategy for UAN are the very active area for the researchers. The harsh aquatic behavior makes terrestrial routing strategies unsuitable for UAN. Recently, many studies, reviews and theoretical analyses have been carried out to understand the various aspects of appropriate designs of UAN routing protocols. Many protocols based on Ad hoc on-demand Distance Vector (AODV), Dynamic Source Routing (DSR) and other routing protocols have also been investigated for underwater use. The review on the applicability of standard routing protocols like proactive, reactive and geographical routing in UAN is described in Akyildiz *et al*. (2006). Authors explained the unfitness of these protocols as these schemes offer a large signaling overhead, probable link failures, high latency, high-frequency band used in GPS and incessant dependency of control bits. Thus, not fit for underwater acoustic network and it is essential to develop novel protocols that mitigate all the said effects and offer reliable implementation for the underwater acoustic network layer. It was emphasized that 3D underwater localization with low complexity solution is very significant for the estimating current position and subsequent routing. In this review, various proposed protocols like VBF, central polled manager, routing through optical transmission, etc. are also considered unsuitable for UAN. Nevertheless, importance of two phases routing solution as the suitable candidate for UAN has been demonstrated in terms of virtual circuit technique. In first phase, node-disjoint primary and backup, data are configured while in second phase, local repair of nodes for link failures is carried out. Furthermore, design of various issues of delay sensitive/insensitive applications with the concept of efficient energy consumption, low signaling overhead, few link failures and effective localization for deployment of UAN are also explained.

Another good survey based on clustered and fully distributed routing topologies for UAN has been carried out in Chitre *et al*. (2008). The study explains the importance of location aware routing for dynamic AUV networks (i.e., altered version of DSR), optimized delay sensitive protocols and necessary requirement of network coding in UAN. Network coding is used to optimize the network layer design, permit to design energy-efficient, robustness, scalability and adaptive nature protocols. Due to ever increasing applications, networking of mobile AUVs is currently a very active area of research. The mobility and ad-hoc requirements for such networks pose many challenges. In Jiang (2008), virtual circuit routing is considered as the most convincing protocol for underwater acoustic as compared to packet switched routing schemes. Author explained the inflexibility problem of this scheme more severely resist its use in underwater networks. In order to increase the flexibility of this scheme for UAN is being currently analyzed and studied by many researchers.

DESIGN OF DESIGN OF TRANSPORT LAYER

For any communication network, transport layer considers as a higher-level platform that ensures the reliability of network by error detection, message acknowledgement, flow and congestion control. Transport layer only requires the communication link without knowing the components of a link. In the analysis of state of the art protocol by Akyildiz *et al.* (2006), many design aspects and problems of the transport layer are discussed for futuristic development of UAN. In underwater environment, both rate based and windows based TCPs (Transfer Control Protocols) are considered inappropriate for implementation due to the highly dynamic and long RTT (Round Trip Time). First transport protocol for UAN, SDRT (Segmented Data Reliable Transport), was a very inspiring step towards higher layer's design. However, the overhead problem, imposed due to tornado coding/decoding, redundant packets from the large window size, ignorance of shadow zones and exclusion of definite means for the end-to-end data reliability, will require further improvement in this design. It is deliberated in this study that proper design of a transport layer should be based on consideration of minimum energy consumption, continuous forwarding of packet sequence, adaptive response to local conditions, flexibility to interact with lower layers, reliability, handling in shadow zone and low computational overhead.

OTHER DESIGN ASPECTS

In addition to all abovementioned advancement and studies following design aspects for UWAC and networking have also been investigated.

Covert multi-band OFDM communication: In OFDM based UWAC systems, one of the major problems is the higher peak-to-average power ratio due to the superposition of signals of all sub-carriers. The constructive accumulation of these signals makes peak power much higher than the average power. Thus, more power requires for power amplifier and these random peaks lead to make the low efficiency system. In order to avoid this effect, the OFDM system having a more expensive power amplifier that can be capable to give high linearity and a wide dynamic range is required. Many PAR reduction techniques have been proposed based on pre-coding, clipping method, selective mapping method, proper insertion of interleaves, etc.; however, in each method, side information along with actual information is required that cause transmission rate slower. In Han *et al.* (2004), the authors described a novel approach based on the signal set expansion that reduces PAR effectively without transmitting any extra information with transmitting signal, but it offers more complexities and overheads with the level of reduction. Another method by Zhang *et al.* (2010) that utilizes additional DFT operation in OFDM system considerably reduces the PAR and provides the excellent results. The outstanding simulation and experimental results prove the applicability of this method in complex underwater environments in the cost of little overhead. Figure 3 shows the effect of DFT spread OFDM technique.

Cross layer design: Like ground based RF communication, the effectiveness of cross layer design approach to improve the UAN efficiency has been described by Akyildiz *et al.* (2006) and Jiang (2008). The cross layer design offers the useful interaction between the various layers for optimized usage of resources and effective data transmission. However, this design requires in-depth knowledge of different layers and appropriate coordination. This type of design that relies on the continuous interactions from physical components to various protocols design will be very challenging due to extremely complex behavior of ocean. Unlike RF communication, UAN bears many problems like limited bandwidth, long propagation delay, frequency selectivity issue and dynamic channel. Therefore, designing of communication network that can adaptively deal with environmental changes at every layer and offer utilization of energy more efficiently would be best possible solution. Cross layer approach is very appealing scheme and it will definitely provide the standard network design that could be the robust candidate against many fast varying aquatic environment.

Normal mode decomposition: In the current researches, coherent OFDM method has been considered as the most appropriate method for UWAC. However, in addition to OFDM mo feasibility study on the decomposition of normal mode as a preprocessing step in UWAC has been investigated by Morozov *et al.* (2010). Same like multicarrier modulation this method is also based on shortening of channel delay spread to mitigate the effect of ISI and channel induced fluctuation by rapid adaptation. Conversely, this method is very sensitive to bathymetry and therefore, only applicable to shallow-water communication. The experimental results showed that mode filtering method is suitable for low frequency communication (100~300 Hz) and for long distances, it could get good BER with simple demodulator design. The method showed very promising results but due to frequencies and depth limitations, coherent OFDM based system is still more demanding candidate for UWAC physical layer.

Capacity of network: Capacity analysis is very necessary for network planning and optimum management of resources in the particular layer. Many analyses for optimal design of physical layer rely on single carrier-based UWAC has been carried out. Capacity analysis of multicarrier underwater (i.e., OFDM) acoustic system was first investigated in Srinivasan and Rodoplu (2008) based on average path loss and frequency-dependent absorption. The design allows multiple-layer architecture and solves the problem by utilizing different reuse numbers adaptively with the task of maximization of data rate per mobile user and the minimization of transmit power per base station. The simulation results explain the significance of the above analysis with limited consideration as other effects like Doppler shift and carrier synchronization are not covered in this analysis.

Effects of bottom layers: Effects of range inhomogeneous bottom layering on shallow-water low frequency communication have been analyzed in by Knobles *et al.* (2010) through parabolic equation model simulation. Various parameters like sound speed, attenuation, seismic and geophysical information are input to the finite parabolic equation propagation model to analyze the effects. Experimental results show that sea bottom which affects shallow-water transmission mainly depends upon the depth of modal diffusion and the interference area between water residue and inhomogeneous layers. The sound speed ratio at surface and existence of the operational frequency band that depends on the communication distance are considered essential to monitor the range-dependent layering effect of the seabed.

Securing UAN: In Domingo (2011), various possible aspects regarding the security of UWAC and networking have been demonstrated. A need of robust security mechanism that can handle the unique characteristics of underwater channel is highlighted and many attacks with their counter measures are comprehensively explained. Author explains the major reasons of low BER acoustic link in terms of long multipath effects, extreme bandwidth, dynamic channel and refractive properties of sound. Effects like jamming, wormhole, sinkhole, Sybil's attack, etc. and main components of security in terms of authentication, confidentially, integrity and availability have been discussed. The author emphasized on the importance of securing steps and pinpointed the possible challenges for safe time synchronization, localization and routing strategies. This study will be very beneficial for the designing of secure UWAC and networking systems that can guarantee the good performance under complicated sea environment.

RELEVANCE TO WORK

Relevance to work can be divided into three stages: Physical layer design and development through low complex coherent MIMO-OFDM UWAC system. Simulation work and experimental analyses based on point to point SISO, SIMO and MIMO OFDM systems may be carried out with the task of robust design against severe challenges and real-time implementation. Investigation of design issues and practical implementation of MAC protocol that can take full advantage of OFDM based modems and can be well suited for harsh underwater environments would be the second stage of work. Finally, network design issues, specifically the study based on the exploration of possible flexibility in the virtual routing schemes may be carried out. Provision of the cross layer design aspects may also be analyzed in any relevant work for the efficient joint resources management against dynamic oceanic behavior.

CONCLUSION

In this study, an overview of the recent research development and design aspects of Underwater Acoustic Communication and Networking has been presented. Initially, the challenges' posts by the complex oceanic channel are analyzed. Recent advancement in terms of physical layer design has been investigated in details and coherent MIMO-OFDM system is considered as a suitable candidate for UWAC. Problems relevant to real-time implementation of UAN are then highlighted for the design from MAC protocols, network layers to the transport layer. Other design aspects, including the most appealing cross layer approach along with the security concerns are also reviewed for the development of efficient and reliable underwater acoustic sensor networks. The key purpose of this study is to provide outlines of recent advancement in the development of advanced techniques in the field of UWAC and networking for the state of the art oceanic information exchange and other aquatic exploration applications. This survey can act as a requisite platform for the individuals who want to involve in the research of this emerging field.

ACKENOWLEDGMENT

The author is very thankful to the Chinese Scholarship Council (CSC) for awarding Scholarship, Prof. Qiao Gang for his valuable supervision and Mr. Khurram Mahboob for their precious guidelines in writing this study.

REFERENCES

Akyildiz, I.F., D. Pompili and T. Melodia, 2006. State of the art in protocol research for underwater acoustic sensor networks. Proceedings of WUWNet'06, 2006, pp: 7-16.

Arshad, K., 2003. Channel estimation in OFDM systems. MA. Thesis, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudia Arabia.

Carrasosa, P.C. and M. Stojanovic, 2010. Peer-reviewed technical communication: Adaptive channel estimation and data detection for underwater acoustic MIMO-OFDM systems. IEEE J. Ocean Eng., 35(3): 635-646.

Chirdchoo, N., W.S. Soh and K.C. Chua, 2008. RIPT: A receiver-initiated reservation-based protocol for underwater acoustic networks. IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Underwater Wireless Commun. Networks, 26(9): 1744-1753.

Chitre, M., S.H. Ong and J. Potter, 2005. Performance of coded OFDM in very shallow water channels and snapping shrimp noise. Proceedings of MTS/IEEE OCEANS, 2, pp: 996-1001.

Chitre, M., S. Shahabudeen, L. Freitag and M. Stojanovic, 2008. Recent advances in underwater acoustic communication and networking. Proceedings of OCEANS'08 MTS/IEEE Quebec Conference, National University of Singapore, Sep. 15-18, pp:1-10.

Domingo, M.C., 2011. Securing underwater wireless communication networks. Wirel. Commun., IEEE, 18(1): 22-28.

Han, S.H. and J.H. Lee, 2004. Peak to average power ratio reduction of an OFDM signal by signal set expansion. Proceedings of IEEE conference on communications, July, pp: 867-871.

Huang, J., C.R. Berger, S. Zhou and J. Huang, 2010a. Comparison of basis pursuit algorithms for sparse channel estimation in underwater acoustic OFDM. OCEANS 2010 IEEE-Sydney, 24-27 May, pp:1-6.

Huang, J., J.Z. Huang, C.R. Berger, S. Zhou and P. Willett, 2010b. Iterative sparse channel estimation and decoding for underwater MIMO-OFDM. EURASIP J. Adv. Signal Process., 2010: Article ID 460379:1-8.

Jiang, Z., 2008. Underwater acoustic networks-issues and solutions. Int. J. Intell. Controal Syst., 13(3): 152-161

Kang, T. and R.A. Litis, 2008. Matching pursuits channel estimation for an underwater acoustic OFDM modem. Proceedings of IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP, pp: 5296-5299.

Khan, R., Q. Gang and W. Wei, 2011. A review of underwater acoustic communication techniques. Proceedings of ICMET, pp: 8.

Knobles, D.P., J.A. Goff, R.A. Koch, P.S. Wilson and J.A. Shooter, 2010. Effect of inhomogeneous sub-bottom layering on broadband acosutic propagation. IEEE J. Ocean Eng., 35(4): 732-743.

Li, B., S. Zhou, M. Stojanovic, L. Freitag and P. Willett, 2008. Multicarrier communication over underwater acoustic channel with nonuniform doppler shifts. IEEE J. Ocean Eng., 33(2): 198-209.

Li, B., 2009. Multicarrier modulation for underwater acoustic communication. Ph.D. Thesis, University of Connecticut, CT 06269.

Li, B., J. Huang, S. Zhou, K. Ball, M. Stojanovic, L. Freitag and P. Willett, 2009. MIMO-OFDM for high rate underwater acoustic communication. IEEE J. Oceanic Eng., 34(4): 634-644.

Morozov, A.K., J.C. Preisig and J.C. Papp, 2010. Investigation of mode filtering as a preprocessing method for shallow-water acoustic communication. IEEE J. Ocean Eng., 35(4): 744-755.

Nasri, N., L. Andrieux, A. Kachouri and M. Samet, 2009. Behavioral modeling and simulation of underwater channel. J. WSEAS Trans. Commun., 8(2): 259-268.

Palou, G. and M. Stojanovic, 2009. Underwater acoustic MIMO OFDM: An experimental analysis. OCEANS, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges, 26-29 October, Sea Grant College Program, MIT, Cambridge, MA, USA, pp: 1-8.

Parrish, N., S. Roy and P. Arabshahi, 2008. Poster abstract: OFDM in underwater channel. Proceedings of the 3rd ACM Workshop on Underwater Networks (Mobicom 2008), San Francisco, CA, Sept. 15.

Srinivasan, B. and V. Rodoplu, 2008. Capacity of underwater acoustic OFDM cellular networks. Department of Electrical and Computer Engineering, M.S. Thesis, University of California, Santa Barbara, CA 93106-9560.

Stojanovic, M., 2006. Low complexity OFDM detector for underwater acoustic channels. Proceedings of IEEE OCEANS Conference, Sep. DOI: 10.1109/OCEANS.2006.307057.

Stojanovic, M., 2008. OFDM for underwater acoustic communications: Adaptive synchronization and sparse channel estimation. Proceedings of ICASSP, pp: 5288-5291.

Stojanovic, M., 2009. MIMO OFDM over underwater acoustic channels. Proceedings of the 43rd Asilomar Conference, Signals Syst. Comput., Nov, pp: 605-609.

Syed, A.A., W. Ye and J. Heidemann, 2008. T-Lohi: A newclass of MAC protocols for underwater acoustic sensor networks. Proceedings of IEEE Infocom, Pheonix, AZ, April, pp: 789-797.

Tao, J., 2010. Robust receiver design for RF communication and underwater acoustic communication. Ph.D. Thesis, University of Missouri, Columbia, MO 65211.

Thottappilly, A., 2011. OFDM for underwater acoustic communication. Department of Electrical Engineering, M.S. Thesis, Virginia Polytechnic Institue and State Univeristy, Blackburg, Virginia.

Tianyu, S., Y. Zhaokai, L. Yu, S. Guiqing, H. Haining and Z. Chunhua, 2010. A coherent underwater acoustic communication system based on joint iterative equalization and decoding algorithm. Proceedings of IEEE Youth Conference on Information Computing and Telecommunications (YC-ICT), Nov, pp: 73-76.

Tu, K., D. Fertonani, T.M. Duman and P. Hursky, 2009. Mitigation of intercarrier interference in OFDM system over underwater acoustic channels. OCEANS 2009- EUROPE, Arizona State Univ., Tempe, AZ, USA, pp:1-6.

Wang, Z., S. Zhou, G.B. Giannakis, C.R. Berger and J. Huang, 2010. Frequency-domain oversampling for zero-padded OFDM in underwater acoustic communication. Proceedings of GLOBECOM, pp: 1-5.

Weijie, S., S. Haixin, C. En and Z. Younghuai, 2011. SNR estimation algorithm based on pilot symbols for DFT-spread OFDM systems over underwater acoustic channels. J. Convergence Inf. Technol., 6(2): 191-196.

Zhang, Y., H. Sun, E. Cheng and W. Shen, 2010. An underwater acoustic implementation of DFT-spread OFDM. EURASIP J. Adv. Signal Process., 2010: Article ID 572453.

Zhou, Z., S. Le and J.H. Cui, 2010. An OFDM based MAC protocol for underwater acosutic networks. Proceedings of WUWNet'10, 2010: 1-8.