Review

Full Duplex Physical and MAC Layer-Based Underwater Wireless Communication Systems and Protocols: Opportunities, Challenges, and Future Directions

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Abstract: Underwater wireless communication has gained a great deal of attention in the last couple of decades because of its applications in the military, industrial, and monitoring sectors. Despite the extreme physical and MAC layer difficulties, acoustics are used for various applications among the various modes of underwater communication technologies used. While significant research efforts have been made to address these issues, the bottleneck remains in achieving high bandwidth, high throughputs, and data rate. Researchers have begun to look into full duplex (FD) implementation to improve bandwidth efficiency and increase data rate and throughput. Users can send and receive data simultaneously over the FD links, maximizing bandwidth utilization and increasing throughput. As a result, we thoroughly reviewed various FD physical layered UWAC systems and MAC layered protocols for underwater communication. The various problems that the aforementioned systems and protocols have faced, as well as the solutions suggested in previous works to solve each problem, are also highlighted. Various metrics are used to compare the performance of various physical layered FD systems and FD MAC protocols. We also explore some of the open research questions in these FD-physical layered and MAC layered protocols, as well as future research directions. Based on ample information, we suggest a cross-layered architecture based on various IBFD-SI cancellations, DA-CSMA, and FD-MAC protocols. This review provides a broad view of the current FD physical and MAC layered protocols based on acoustic communication, as well as recommendations.

Keywords: self-interference (SI) cancellation; FD-cooperative-UWAC systems; spread spectrum (SS); FD-MAC protocols; contention-free; contention-based; hand-shaking (HS); random access; quality of service (QoS)

1. Introduction

Underwater wireless communication has found considerable attention during last couple of decades because of its applications in the field of military, commercial, and monitoring applications. Among the different modes of communication technologies tried for underwater, such as acoustics [1,2], magneto-inductive [3], radio frequency, and optics [4], acoustics are applied for applications that require long range communication despite the severe physical layer challenges. Serious research efforts have been carried out to improve UWAC technology [5–9] to deal with these challenges, however, achieving high bandwidth and data rate still remain bottlenecks in UWAC advancement. Learning and borrowing from terrestrial networks, to maximize the bandwidth efficiency, increase data rate and throughput researchers have started to explore full duplex (FD) implementation. Users can send and receive data at the same time using FD links in the complex underwater environment, and they can listen to their neighbors' transmitted data using FD links [10]. Since

FD links consider the projected traffic load, they increase network bandwidth efficiency by reducing the effect of under-utilized channels on system throughput and traffic latency [11]. Due to major physical changes in the ocean, the FD-UWAC channel faces challenges such as synchronization and delays, self-loop and SI, LTI, noise, attenuation, multipath effects, and Doppler spread, limited channel power and bandwidth, low bandwidth utilization, collisions, and hidden and exposed terminal problems [12,13]. Furthermore, limited bandwidth and large propagation delay problems in the FD channel cause frequency fading, which affects control timings [14]. As a result, this paper reviews various FD physical layered UWAC systems and MAC layered protocols for underwater communication in great detail. The advantages and difficulties that the above systems and protocols have encountered are also highlighted. Different metrics, such as spectral efficiency, BER, transmission range, and data rate, are used to compare the performance of various physical layered FD systems. Similarly, a comparison of various FD MAC protocols is conducted using various metrics such as throughput, delay efficiency, energy efficiency, transmission rate, and data rate. In terms of the physical and MAC layers, Figure 1 depicts how the aforementioned systems and protocols are classified.
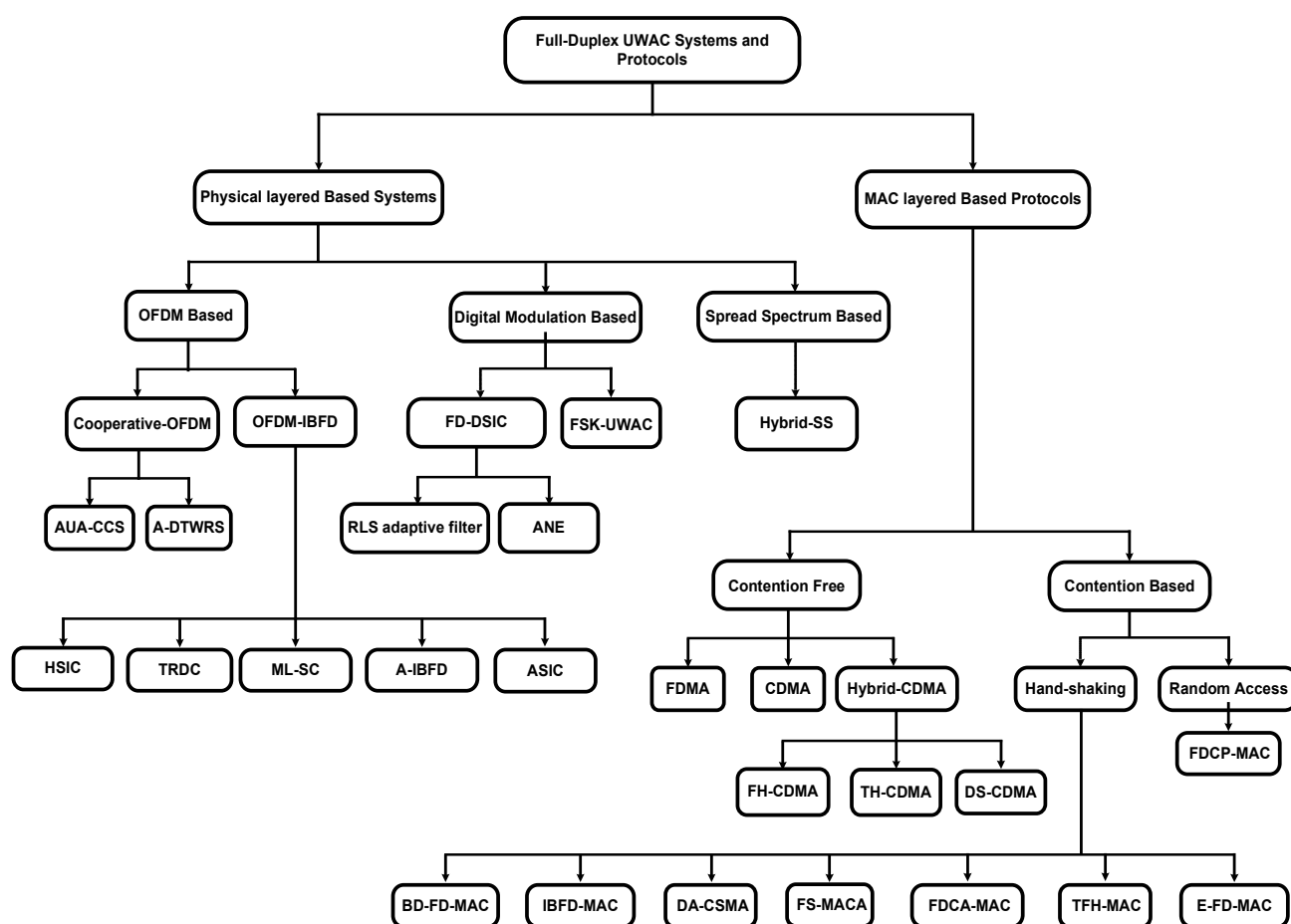
Figure 1. Classification of full-duplex physical layered UWAC systems and MAC layered protocol.

Motivations and Contributions

A physical layer for the UWAC channel is needed to ensure adequate operation in various UW environmental classes [15,16]. The efficient operation of FD-UWAC systems using the physical layer necessitates a variable quality of service (QoS) as well as limited bandwidth systems. Many challenges confront FD physical layer-based systems, including synchronization and delays, self-loop and SI, LTI, noise, attenuation, multipath effects, and Doppler spread. To address these issues, researchers have developed various FD phys-

ical layer-based systems, which are divided into three categories: OFDM-based, digital modulation-based, and spread spectrum-based, as shown in Figure 1. The most promising physical layer for FD-UWAC systems is OFDM, and various OFDM-based systems have been developed. Cooperative OFDM systems are used to combat asynchronous time issues that occur between groups of nodes/relays, which limit the efficiency of OFDM-based systems, increase relative delay and fading, and trigger ICI [17,18]. Similarly, these system are used to combat the low spectral efficiency [19]. To deal with the problem of insufficient bandwidth, IBFD-OFDM systems allow for the most efficient use of the available bandwidth [20,21]. These systems, however, suffer from a high peak-to-average-power ratio (PAPR) due to the use of OFDM as a modulation technique. Furthermore, self-interference limits IBFD-OFDM systems, and various systems (e.g., HSIC [20], TRDC [22], ML-SC-IBFD [23], and A-IBFD [24]) have been developed to resolve this issue. SI cancellation is the goal of digital modulation-based FD systems, and they are classified as such. The proposed RLS-adaptive filter digital modulation systems are based on a digital SI cancellation scheme [25–28], substantially improves its efficiency. The addition of fast convergence, high numerical stability, and low computational complexity are all advantages of these schemes. However, these UWAC systems have issues with far-field interference cancellation and transmission rage. The FSK based digital modulation FD systems are energy-efficient, capable of transmitting over longer distances with long battery life, and safe data transmission [29], but they are complex and incapable of dealing with multipath interference, necessitating further research in this field. Spread spectrum-based FD systems has multiple access capabilities for different users. Further, the low probability of detection (LPD) has been addressed using spread spectrum. Hence, researchers showed interest in direct sequence spread spectrum as a result of these advantages, and it was used in various FD-UWAC systems, where it demonstrated significant efficiency by reducing the effects of fading, noise, jamming, and self-interference [30–32]. A hybrid SS approach is often used in order to establish an FD link connection between multi-user modems for the transmission of data streams and to preserve synchronization between the simultaneously received signals [33].

MAC protocols for underwater acoustic communication have been developed by researchers over the last few decades. The vast majority were based on terrestrial contact protocols [34]. The reformed protocols significantly improved the underwater network's performance in terms of service quality and energy efficiency [34,35]. However, time synchronization, low bandwidth usage, collisions, hidden and revealed terminal problems, and significant delays plague the developed underwater acoustics MAC protocols. Researchers have developed various FD MAC layered-based UWAC protocols to resolve these issues, which are divided into contention-free and contention-based protocols, as shown in Figure 1. The contention-free FD MAC protocols used various methodologies to protect the network from massive collisions, frequency selective fading, and improved transmission efficiency. The contention-free FDMA-based FD-MAC protocol offers a fast and straight-forward method of channelization for available bandwidth, but it is unable to handle the large number of UW nodes, resulting in low bandwidth utilization and frequency selective fading problems, resulting in substantial data loss.

The contention-free CDMA based FD-MAC protocols (e.g., FH-CDMA, DS-CDMA, and TH-CDMA) have been proposed to address the issues faced by the FD-FDMA based protocols, and showed substantial bandwidth benefits. These protocols, however, have a few minor hardware problems. In contention-based FD-UWAC protocols, users compete with one another for channel access to send their data. The user who wins the contention takes control of the medium for a set period of time, while the others remain silent and wait for a free channel to appear. Contention-based FD-MAC protocols are attractive because of their improved throughput, energy efficiency, and robustness, but these advantages fade as network traffic loads rise, resulting in massive data collision and thus increased energy consumption [35,36]. Handshaking-based and random-access-based FD MACs were proposed to fix these issues. The handshaking-based BD-FD-MAC protocol successfully resolves

the problem of long propagation delays, which take a long time to complete an effective transmission and reduce FD-MAC protocols throughput efficiency [36]. This protocol has been implemented in a simulation environment; however, it must be implemented in a practical underwater environment.

The IBFD-MAC handshaking protocol addresses issues including power consumption, unexpected node collisions, long propagation delays, and low data rates [35]. By resolving the hidden and exposed terminal problem, as well as improving data collision elimination, the hand-shaking DA-CSMA protocol significantly increased performance. The handshaking DA-CSMA protocol significantly improved efficiency, by resolving the hidden and exposed terminal issue, as well as improving data collision elimination. In the future, it will be crucial to test its robustness on a large network, even if it is only implemented for 10 nodes randomly distributed in a square km underwater environment. The handshaking FS-MACA protocol is based on the future scheduling (FS) handshaking (HS) mechanism scheme [37]. Scheduled procedures and future negotiations between the sender and receiving section ensure data transmission in the HS system. The physical channel is split into two parts, one for real data transmission and the other for control packet negotiation, resulting in increased throughput and reduced interference while achieving FD communication. This protocol is unable to handle long propagation delays and suffers from extreme throughput degradation because it does not use time synchronization.

The handshaking FDCA-MAC UWAC protocol mentioned in [34] is based on the principle of transmitting and receiving on the same frequency at the same time, which reduces hidden and exposed terminal problems and enables FD-UWAC modems to achieve high throughput. In the future, it will be necessary to test its viability in both a dry and a salty climate. The proposed handshaking-based TFH-MAC protocol significantly reduces SLI, a common issue with FD UWAC systems. When used in a wide network, however, this protocol is unable to handle long propagation delays, resulting in reduced performance. The E-FD-MAC, which is based on handshaking, allows the FD channel to exchange data packets simultaneously in the shortest amount of possible time. This protocol allows the source and destination to exchange data using sensed information without being affected by accidental collisions, resulting in significantly higher throughput and shorter propagation delays [38]. Random access MAC protocols are designed to send and receive data between multiple nodes in a random fashion without any control or HS mechanism. This increases the likelihood of high collisions and massive energy consumption, and hence, a self-organized FDCP-MAC protocol for multi-hop ad hoc UWAN network has been developed [39]. With the aid of a fixed time HS and a time stamped conflict resolution mechanism, this proposed protocol can more effectively use the channel and prevent massive collisions at high network loads. Additionally, this protocol increases throughput while decreasing collision rates.

Our contributions are summarized as follows:

- We reviewed various FD systems and protocols for underwater communication and classified them based on the Physical and MAC layers. The impact of various features on the FD systems and protocols discussed is thoroughly explained. This survey looks at various methodologies for improving the quality and efficiency of these reliable FD systems and protocols, with the aim of further expanding the implementation of these systems and protocols in the future.
- We contributed by comparing different FD-physical layer-based UWAC Systems in terms of different metrics including spectral efficiency, BER, transmission range, and data rate, as well as implementing these protocols in different environments. The advantages and disadvantages of these protocols are also discussed.
- We contributed by comparing various FD MAC protocols based on throughput, delay efficiency, energy efficiency, transmission rate, and data rate. These protocols' advantages and disadvantages are discussed in detail.

- We contributed by laying out a number of significant challenges that affect the performance of FD-UWAC systems and MAC layered protocols, all of which must be carefully addressed as these systems are built.
- To the best of our knowledge, some new open issues and potential research directions are listed, which will aid in the advancement of the aforementioned FD systems and MAC protocols.

2. Physical Layer-Based Full-Duplex Underwater Acoustic Communication Systems

Since the FD-UW channel is divided into different classes, a physical layer for the UWAC channel is needed to ensure adequate operation in various UW environmental classes [15,16]. The physical layer can be used to demonstrate theoretical acoustic wave propagation concepts, impulse response measurements, and signal limitations in the underwater environment. The efficient operation of FD-UWAC using the physical layer necessitates a variable quality of service (QoS) as well as limited bandwidth systems. Many challenges confront FD physical layer-based systems, including synchronization and delays, self-loop and SI, noise, attenuation, multipath effects, and Doppler spread. Researchers created FD physical layer-based systems to address these problems, which are divided into three categories: OFDM based, digital modulation-based, and spread-spectrum-based.

2.1. Challenges Faced by FD Physical Layered UWAC Systems

Some significant challenges faced by researchers in the design of FD-physical layered UWAC-based protocols are listed in this section, as well as the solutions proposed in previous works to solve each problem.

Synchronization: Due to the low propagation speed of sound, the existence of large delays at the receiver end is a substantial challenge to accurately synchronize the UWA communication systems. Additionally, this causes huge delays at receiving section of the specific relay or node [19]. Maintaining precise synchronization between the nodes/relays in order to receive signal simultaneously as it passes from source to destination becomes a substantial challenge [19,40]. To address the issues of synchronization and delays, various modulation schemes have been used in various protocols. The FD-OFDM-based modulation schemes, for example, are implemented by lengthening OFDM blocks [40]. In the FD-UWA communication system, another FD-OFDM-based scheme implemented the two-way-relay system, which significantly reduced the huge delays and comfortably allowed the synchronization between node/relays [19].

Self-interference (SI): The efficiency of FD-UWAC protocols is influenced by two types of interference: Multiple reflection interference (MRI) and SLI [22–24,41]. The SLI has a significant impact on the performance of IBFD-UWAC systems, which usually appear after a long period of time. The IBFD-UWAC protocols struggle to suppress the SLI because of the longer delays [23,41–43]. Various methods have been developed to suppress SLI, such as [14], which implements a method that uses both analog and digital cancellation to reduce SLI. Soft-decision feedback turbo equalization (SDFE) is used to remove ISI and residual self-interference in [22]. However, the SI problem remains a significant challenge for the protocols listed.

Local transmission Interference (LTI): Since FD-UWAC protocols are implemented using modems, they experience their own transmission interference (i.e., LTI), which is caused by the use of an omni-directional transducer in the modems [33]. Acoustic baffles are used between the transmitting transducer and the receiving sensor vectors in a few methods to remove LTI. A distinction between the omni-directional transducer and receiving vectors is maintained by inserting a rod between them for more effective suppression of LTI. The methods described above also assist in improving the received signal's signal-to-noise ratio (SNR).

Noises: Noise is a widespread and fundamental issue that has a significant impact on the efficiency of all types of underwater FD physical layered UWAC systems [22,41]. Ambient noise has a major impact on FD-physical layer dependent systems at the receiver

section, where an increase in noise power (dB) is directly proportional to an increase in residual analog interference. To reduce this, the IBFD-UWAC framework [41] introduced a powerful analog self-interference cancellation scheme.

Attenuation: The long transmission range of the UW acoustic signals induces attenuation, converting the acoustic signal to heat [44]. Furthermore, in FD-physical layer-based UWAC systems [45], high frequencies are used to increase data rates, resulting in a serious attenuation problem [44]. The presence of sound absorbing obstructions, as well as changes in shallow sea water salinity and temperature in the FD physical layered dependent UWAC systems, are two other common causes of increased attenuation.

Multipath Phenomenon: Reflections from the sea's surface and bottom induce the multipath effect, which affects the transmitted signal's phase and amplitude [46]. Due to the availability of limited FD-UWAC channel bandwidth, ISI is caused by time-varying multipath effects [46,47]. The multipath effect occurs in shallow water interaction due to the surface reflection and refraction effect [48], causing substantial end-to-end delays and an increase in bit error rates [32,49]. Furthermore, the increased depth's multipath effect has an influence on the UW communication channel's vertical and horizontal link configuration. Vertical links have little time dispersion, while horizontal links have a lot of multipath spreading [37,50].

Doppler Spread/Doppler Shift: The Doppler change in frequency is caused by the continuous movement of physical layered dependent UWAC sensors at the receiver and source sides [48,51]. The effect of Doppler shift can be easily reduced by preserving sub-carrier spacing, but this method degrades spectral efficiency as well as data rate, and this area needs to be explored further [48,52].

2.2. OFDM Based UWAC Systems

The most promising physical layer for underwater acoustic network (UWAN) communication is orthogonal frequency division multiplexing (OFDM). There has been a lot of research done in this field. However, the use of OFDM for FD communication is still being researched. The OFDM technique divides the available frequency band into orthogonal subcarriers. Symbols are emitted concurrently by these mutually orthogonal subcarriers with overlapping frequency bands [53,54].

The OFDM system has been proven an efficient modulation technique for the terrestrial communication system [55]. However, if the signal has to pass through a multipath channel, such as the UWAC channel, orthogonality suffers from ICI. To remove ICI, a guard interval was added after each individual channel in the OFDM system, as seen in the diagram, as shown in Figure 2.
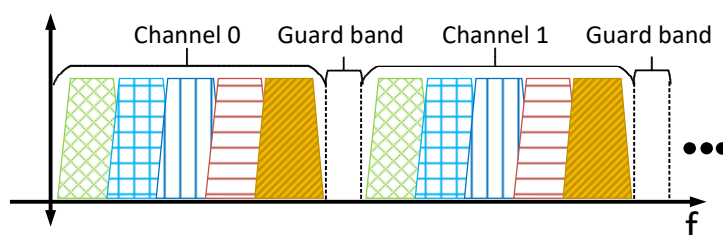
Figure 2. Frequency domain of OFDM system.

Furthermore, selective Automatic Repeat reQuest (ARQ) is needed to improve the reliability of the FD-OFDM channel in difficult channel conditions [55]. Other parameters for the FD-OFDM channel are necessary for effective operation in the physical and data link layers, as shown below.

- The OFDM signal's entire bandwidth should cover all the data transmission frequencies, which is dependent on the bandwidth of the mounted transducers [55].
- The inverse fast Fourier transform (IFFT) algorithm is used to make the sub-carriers orthogonal for successful transmission using the UW communication transceiver [16].

- The Doppler distribution f_m of the OFDM channel must be smaller [16,20]. The coherence band-width is denoted by Δf_c, and the rate of signaling I is denoted by W:

$$\Delta f_c > W >> f_m \tag{1}$$

- As shown below, the channel coherence time is denoted by denoted by Δt_c. T_S is the upper limit of the OFDM symbol length, τ_{rms} is the rms access delay and τ_{max} is the maximum access delay:

$$\Delta t_c << T_s < \tau_{rms} \tag{2}$$

- A cyclic prefix is applied to the OFDM symbol to reduce the SNR in the OFDM channel. The symbol length is five to six times longer than the cyclic prefix (CP) period, resulting in a throughput loss of less than one decibel.

2.2.1. Cooperative-OFDM Systems

The asynchronous time issues that occur between groups of nodes/relays limit OFDM-based UWAC FD-systems, increasing relative delay and fading and being the cause of ICI. As a result, several FD-OFDM-based underwater cooperative diversity systems have been developed in the literature to address the aforementioned issues. For instance, in amplify and forward (AF) cooperative underwater communication systems, a new effective OFDM is used to combat the issue of time delays [23], which encounter the asynchronous issue at the receiver [17,18]. Short and manageable CP was used at the transmitter, and a low-complexity Viterbi decoder was used at the receiver [40].

- **AUA-CCS**. A pairwise error probability (PRP) method is used in AUA-CCS to achieve maximum spatial diversity and time-invariant channels. The described protocol has been found robust to ISI, reduces asynchronous time issues, and boosts the spectral efficiency performance of time-varying channels [23]. However, despite having a fixed power amplifier factor, this protocol is not energy efficient [40,56].
- **A-DTWR**. The A-DTWR FD-OFDM based system is proposed in [19] to combat the issues of low spectral efficiency and wide delays in time-varying frequency-selective channels in OFDM based FD-UWAC cooperative communication systems. Two users can exchange data using two relays in this system, and simultaneous transmission is carried out in FD fashion between the users. However, through each relay, the propagation delay and time errors (two forms of time errors) can be observed at the receiver [19,57]. The first error occurs when the user's signals are misaligned on a single relay during the MAC phase, and the second error occurs when the system's two relays send the same copy to the destination at different times to a single user. To address these issues, a new full-duplex analog network coding (FD-ANC) system is being developed at the receiver section, which employs proper signaling and the Viterbi algorithm on each sub-carrier block. For the extraction of delay diversity from the two identical copies sent from the source to the destination, the Viterbi algorithm is used.

2.2.2. OFDM-Based IBFD Systems

Researchers introduced the IBFD-OFDM-UWAC systems to allow maximum use of available bandwidth to combat the problem of insufficient bandwidth in previously proposed UWAC systems and thus showed significant results [20,21]. Despite their numerous benefits, the OFDM-IBFD-UWAC systems suffer due to a PAPR caused by the use of OFDM as a modulation technique. Researchers have used the clip-off signaling technique before amplification to reduce the signal PAPR [23]. Furthermore, because of the FD communication path, IBFD-OFDM based UWAC systems suffer from the most severe SI and SLI from nearby transmitters, which reduces the efficiency of the IBFD-UWAC systems [41,58], as shown in Figure 3. After a long time, the SLI appears and is exceedingly difficult to suppress. Reflections from the sea's top and bottom cause multiple reflection interference. In an IBFD-UWAC device, the clipped OFDM signal technique is very useful for estimating

the SI. In recent years, a lot of work has been done to tackle self-interference in IBFD-UWAC systems, which is discussed below.

- **HSIC**. By introducing a hybrid analog and digital cancellation mechanism to predict dynamic range saturation, a novel HSIC scheme has been created to eliminate self-loop and multiple-reflection interferences [20]. The analog SI cancellation is applied before the low-noise-amplifier (LNA) [41]. In addition to the analog to digital converter, the digital SI is used to estimate residual SI (ADC). The proposed scheme uses an IBFD communication framework on FD modems, which dramatically reduces SLI and multiple reflection interference (i.e., interference produced due to reflection from the sea surface and seafloor).

- **TRDC**. Using time-reversal and soft-decision feedback turbo equalization, a novel TRDC automatic cancellation scheme for the elimination of ISI and RSI is proposed (SDFE) [22]. When compared to the previously used scheme, this proposed scheme had a substantial gain of 2.5 dB and demonstrated significant performance by achieving high spectral efficiency.

- **ML-SC-IBFD**. A novel ML-SC-IBFD estimator-based SI channel estimation algorithm is proposed, that takes advantage of sparse constraints and OFDM modulation techniques while using both digital and analog cancellation schemes to suppress the SLI [23]. Experimental results showed that this proposed scheme for IBFD-UWAC demonstrated better BER performance, highly accurate SI estimation, and cancelation performance, as compared to the previous methods. Further, it executed a faster convergence rate than Non-parametric-Maximum-likelihood (NPML), and the lowest level of mean square error (MSE), than that of conventional methods. In contrast to previous methods, experimental results showed that this proposed scheme for IBFD-UWAC demonstrated better BER performance, highly accurate SI estimation, and cancelation performance. It also had a higher convergence rate than Non-parametric-Maximum-likelihood (NPML) and the lowest mean square error (MSE) than traditional methods.

- **A-IBFD**. A new A-IBFD framework has been introduced in [24] to remove two major issues in IBFD-UWAC systems: asynchronous contact and non-linear distortion induced by the power amplifier (PA). In the proposed scheme, the researchers devised two cancellation schemes: analog and digital cancellation [59]. However, the authors primarily concentrated on digital cancellation because analog cancellation has an indirect effect on the output of the digital canceler technique's signal-to-interference-ratio (SIR). We discovered that by synchronizing the intended signal with the addition of a spread spectrum non-overlapping area, an over-parameterization algorithm is used to estimate the non-linear SI channel. The proposed scheme outperformed previous SI cancellation schemes in terms of BER, with the added benefit of faster sparse constraints than the Over-Parameterization based Recursive Least Squares (OPRLS). We discovered that this exclusive research could be expanded in the future to increase the UWAC protocols throughput and spectral performance.

- **A-SIC**. A novel A-SIC mechanism is proposed that uses the normalized least mean square (NLMS) and adaptive self-interference cancellation (ASIC) schemes to prevent SI cancellation [44]. The received signal from the distant node is remodeled using the detected signal, and then the remodeled signal is subtracted from the received signal after the ASIC to obtain the RSI signal, which is then processed using the NLMS algorithm. This entire process is used to increase the ASIC algorithm's ability to suppress SI to an estimated level of ambient noise. Furthermore, un-coded QPSK with OFDM modulation is used to send and receive data between the two IBFD nodes. The experimental and simulation results show that this advanced cancellation scheme effectively reduces SI to ambient noise levels [44].
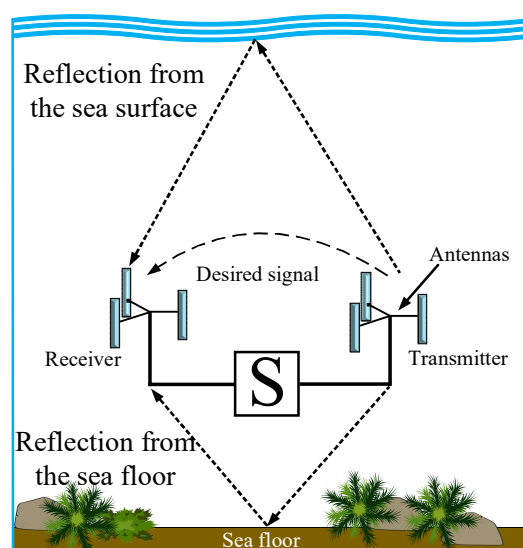
Figure 3. Self-multipath interference of IBFD acoustic system in shallow water.

2.3. Digital Modulation Based Systems

The digital modulation-based FD systems are developed for the analog SI cancellation and digital SI cancellation. These are divided into two categories such as FD-digital self-interference cancellation based and frequency shift keying-based FD-UWAC systems, as discussed below.

2.3.1. FD-DSIC Systems

Due to the high complexity and weak SI cancelation efficiency of the previous FD-UWAC systems, the proposed sparse adaptive algorithms built for estimation of the SI channel and PA nonlinearity in UWAC systems perform poorly [24]. As a result, FD-digital SI-cancellation based UWAC systems have been developed, which can suppress SI more effectively than previously proposed UWAC systems and terrestrial communication systems.

- **RLS-Adaptive-filter**. A less-complex recursive least-square (RLS) adaptive filter with dichotomous co-ordinate descent (DSD) is proposed [25–27], which is based on a digital SI cancellation scheme. In this proposed scheme the PA output is used to recreate the non-linear PA-SI signal, which improves the efficiency of the advanced SI cancellation scheme. Addition of Fast convergence, high numerical stability, and low computational complexity are all advantages of the recursive least-square dichotomous coordinate decent phenomenon. With the PA adaptive filter, the RLS-DSD effectively suppresses SI at 69 dB. Additionally, this proposed scheme cancels the near-field interference signal. These systems also have issues with far-field interference cancellation and transmission rage.

- **ANE**. A novel ANE-based digital cancellation scheme is proposed in [60], in which the PA's output signal serves as a guide for digital cancellation to resolve non-linear distortion in the transmitter and receiver chains. The equalization has been performed by using the basis expansion model (BEM), which can model the inverse of the pre-amplifier response. To achieve a better equalization performance, the proposed scheme uses two cost functions, the mean squared error (MSE) and the other one is derived from the power spectrum of the received signal. These systems have been tested on two water tanks. In the first water tank, artificial non-linear restoration along with the Rapp model has been installed to receive the signal from the hydrophone, but without using the pre-amplifier, and in the second tank hydrophone receives the signal with a pre-amplifier by utilizing the non-linear equalization technique. The second tank shows a better SI cancellation performance of 4 dB by applying the ANE technique.

2.3.2. FSK-UWAC

The UWAC systems based on FD frequency shift keying (FSK) are energy-efficient, capable of transmitting over longer distances with long battery life, and safe data transmission. For instance, in [29], the FSK-based FD-UWAC system is developed while two users communicate using ASCII commands. Every text converted into a string of 7 bits uses the 7-bit ASCII code, and FSK modulation is used to modulate the information between the two users. This FD-FSK-ASCII-based communication system has a data rate of 21 bps and can transmit up to 50 m while using 6.35 W of transmit power per user. The mentioned FSK-based UWAC systems are energy efficient and capable of transmitting over longer distances, but they are complex and incapable of dealing with multipath interference, necessitating further research in this field.

2.4. Spread Spectrum (SS) Based Systems

Low probability of detection (LPD) is highly dependent on input SNR at the interceptor of the signal wave form [61]. The UWAC system that is equipped with SS system, experience huge phase change between the two adjacent data symbols. To accurately detect the phase difference between the UW moving objects SS based systems require highly precise channel equalization, symbol synchronization and high SNR signals [62]. Also, in an extreme fading multipath UWAC channel, SS system has multiple access capabilities for different users. Because of these benefits, researchers became interested in DSSS and used it in various FD-UWAC systems, where it demonstrated substantial performance by reducing the effects of fading, noise, jamming, and self-interference [30,31]. A communication channel is divided into data and control channels in [63,64], and at the physical layer, the control packets were modulated and demodulated using the DSSS method at a frequency of 6–8 kHz.

Hybrid-SS

A hybrid SS approach is used to create an FD communication connection between multi-user modems for the transmission of data streams and to maintain synchronization between the simultaneously received signals [33]. Hybrid spread spectrum technique is created by combining DSSS and code shift keying (CSK). The spread spectrum is used to measure the channel characteristics in the in-phase, while the code phase of sequence in the quadrature channel is used to send data.

2.5. Comparison of Different FD-Physical Layer-Based UWAC Systems

As shown in Table 1, this section provides a detailed comparison of various FD physical layer-based UWAC systems. We also provide a brief overview and implementation of these protocols in different environments, as well as their performance comparison with respect to various metrics such as spectral quality, data rate, BER, transmission range, and SNR.

Table 1. Analysis of physical layer-based UWAC systems.

System Type	Name/Ref.	Modulation	Implementation	Performance Metrics				
				Spectral Efficiency	BER	Transmission Range	SNR	Data Rate
Cooperative OFDM	AUA-CCS [40]	OFDM	Simulation	High	Low	NA	Low	High
	A-DTWRS [19]	OFDM	Simulation	Moderate	High	NA	High	Low
OFDM-IBFD	HSIC [41]	OFDM	Deep sea water	Enhance	NA	Very low	NA	NA
	TRDC [22]	OFDM	Deep sea water	Moderate	Low	High	low	NA
	ML-SC-IBFD [23]	OFDM	Pool water	Enhance	Low	Medium	Moderate	NA
	A-IBFD [24]	OFDM	Pool water	Moderate	High	Medium	High	NA
	ASIC [44],	OFDM	Shallow water	NA	NA	NA	NA	NA
Digital modulation	RLS adaptive filter [25]	BPSK	Water Tank	Very low	NA	Low	NA	Low
	ANE [60]	BPSK	Water Tank	Low	NA	Very Low	NA	Low
	FSK-UWAC [29]	FSK	Laboratory set-up	High	NA	High	NA	Moderate
Spread spectrum	Hybrid- SS [33]	DSSS	Shallow water	High	NA	High	High	Medium

2.5.1. Spectral Efficiency

In comparison to A-DTWR in [19], the OFDM-based FD cooperative system AUA-CCS in [40] greatly improved the performance of time-varying channels and achieved maximum spectral efficiency by inserting a much shorter and more manageable CP at the source. The IBFD communication channel is used in OFDM-based IBFD-UWAC systems such as ML-SC-IBFD [23], A-IBFD [24], HSIC systems [41], and TRDC [22] to improve the system spectral efficiency. In comparison to ML-SC-IBFD [23], A-IBFD [24] and TRDC [22], the HSIC system in [41] demonstrated substantial performance in terms of high efficiency.

Furthermore, the SDFE-based TRDC [22] has a moderate performance in terms of low efficiency as compared to the other systems ML-SC-IBFD [23], A-IBFD [24] and A-SIC [25]. Owing to the fact that the SDFE-based TRDC [22] system employs a hybrid self-interference cancellation scheme, while HSIC [41] employs analog interference cancellation to suppress the interference, and A-SIC [25] employs the NLMS algorithm to suppress the SI signal for the increase in spectral efficiency. The FSK based FD-UWAC systems [29], RLS-adaptive [25] and ANE [60] adopts the FD-UWAC channel, and significantly enhancement the spectral efficiency. However, the FSK based UWAC system in [29] has shown high spectral efficiency compared to other digital schemes such as RLS-adaptive [25] and ANE [60]. The FSK-based UWAC system [29] sends data at a rate of 21 bits per second over a bandwidth of 60 kHz, which improves spectral efficiency. By deploying full-duplex operation between the FD-UWAC modems, the spread spectrum (SS) based Hybrid-SS system [33] achieves higher spectral performance.

2.5.2. Bit Error Rate

The AUA-CC [40] has lower BER values of 10^{-3} and 10^{-4} when using a time-invariant channel. However, due to its delay independent characteristics, the A-DTWR [19] performs significantly better on the time variant channel. Moreover, as fading becomes quicker, the system in [19] experiences more ICI, resulting in a 10^{-1} fold increase in BER. TRDC [22] is a novel automated cancelation scheme that combines time reversal (TR) and soft-decision feedback turbo equalization (SDFE) to remove SI and ISI, resulting in a 10^{-3} improvement in BER. Due to the presence of significant noise, the ML-SC-IBFD [23] system achieves a higher BER of 10^{-1} at lower SNR. However, as the SNR increases, the ML-SC-IBFD reaches a lower BER of 10^{-3}. Furthermore, A-IBFD [24] uses the Over-Parameterization based Recursive Least Squares algorithm (OPRLS) to estimate the nonlinear SI channel, but the BER gain increases by 10^{-1} as the duration of non-overlapping increases up to 35 ms.

2.5.3. Transmission Range

TRDC [22] transmits the signal up to a range of 10 m, while the transmission ranges of ML-SC-IBFD [23] and A-IBFD [24] achieve an effective transmission range of 7.2 m. Apart from that, the HSIC [41] system only transmits signals up to 0.5 m, while the A-SIC [25] system provides no detail about the transmission range. The transmission range of BPSK-based FD-UWAC systems including RLS-adaptive [17,25] and ANE [60] has been tested for low transmission range. However, in [29], the FSK-based FD–UWAC system was evaluated for a longer transmission range of 5 m to 1000 m while maintaining significant energy efficiency and battery life. A Hybrid-SS device based on spread spectrum (SS) [33] achieves 3 km efficient FD-operation between the FD-UWAC modems. More research is required, however, to enhance its robustness by reducing multipath interference.

2.5.4. Signal-to-Noise Ratio

As the SNR approaches higher values, the AUA-CCS [40] and A-DTWR [19] show better BER outputs in the time invariant channel case $f_d T_s = 0$. The SNR output of A-DTWR [19] is substantially better than AUA-CC [40] in the time variant case $f_d T_s = 10^{-3}$, $f_d T_s = 10^{-4}$. The OFDM-based IBFD-UWAC systems such as A-IBFD [24] and ML-SC-IBFD [23] attain higher SNR values of 30 dB and 20 dB, respectively, while TRDC [22] achieves the lowest SNR of 2.5 dB. The hybrid-SS [33] technique is used in a full-duplex

acoustic modem to effectively eliminate local transmission interference and improve the SNR of the received signal.

2.5.5. Data Rate

It is discovered that AUA-CCS system [40] has achieved high data rate values ranging 7.8467 kb/s to 7.9226 kb/s as compared to the A-DTWRS [19], because of its high spectral efficiency. In digital modulation-based FD-UWAC systems, the FSK-based UWAC system [24] offers a higher data rate and greater energy efficiency than RLS-adaptive [25] and ANE [60] systems, as well as longer battery life. To transmit 10 bps data between FD modems, a spread spectrum (SS) based Hybrid-SS system [33] uses DSSS and code shift keying (CSK).

2.6. Implementation of Physical Layer FD-UWAC Systems Using FD Modems

Many companies and researchers have produced a variety of modems that are cost efficient, consume low power, transmit large amounts of data, have a long transmission range, and are highly reliable in the harsh underwater environment [65,66]. These modems, however, are HD and have very poor throughputs. Researchers were drawn to build FD modems because of the high throughput specifications, multi-user capabilities, and field configurability. A physical layer FD multi-user and parameter reconfigurable underwater acoustic communication modem, for instance, was proposed by the researchers [33]. To achieve multi-user acoustic communication (MUAC) with FD, an OFDM plus CDMA device with spread spectrum implementation is used [33]. The modem's performance is hindered by its long program runtime and high power consumption. As a result, algorithms built in [33] must be optimized to minimize program runtime while consuming minimal resources. It is also essential to investigate its robustness in a deep sea environment with a long range and high data rate.

Authors in [45], describes a modern FD high data rate FPGA-based underwater acoustic modem. It was developed to improve the FD-UWA modems' low data rate, limited communication range, and low power efficiency. In this modem, multiple digital modulation techniques are used on a polyvinylidene fluoride PVDF ultrasonic emitter transducer to transmit more precise, safe, and high-quality signals [45]. It operates at a high frequency of 1 MHz with a point-to-point communication connection, with a data transfer rate of 1 Mbps and a BER of 1.4, with the added benefit of consuming less electricity. However, it has some limitations, such as the fact that it performs best over short distances and that the need for digital circuitry and filter optimization is still being investigated [45]. Table 2 compares the performance of FD physical layer-based UWAC modems in terms of BER, efficiency, transmission range, power consumption, and SNR.

Table 2. Comparison of various full-duplex underwater acoustic modems.

System Type	Ref.	Modulation	Data Rate	Implementation	Performance Matrices				
					BER	Efficiency	Transmission Range	Power Consumption	SNR
Physical layer-based FD-Modems	[33]	OFDM	Low	Shallow water	NA	Medium	High	High	High
	[45]	OOK	High	Swimming pool	Low	High	Low	Low	Low

3. Medium Access Control (MAC) Layered UWAC Protocols

When wireless signals propagate through water, while having a very small bandwidth, the established underwater acoustics protocols face various challenges, such as time synchronization, hidden and exposed terminal issue, and very large delays [10,47,67]. The aforementioned issues have drawn researchers' attention to FD-MAC layer-based underwater acoustics communication protocols, resulting in the development of various FD-MAC layered UWAC protocols in the literature. In the following sections, we will look at a variety of FD-MAC layer-based UWAC protocols, as well as the problems they face and the solutions suggested in previous works to solve each problem.

3.1. Challenges Facing by FD-UWAC MAC Protocols

Some significant challenges faced by researchers in the design of FD MAC layered based protocols are listed in this section, as well as the solutions proposed in previous works to solve each problem.

Time synchronization. In the design of an FD-MAC protocol, time synchronization has always been a crucial problem [30,46]. The duty cycling is central to the MAC protocols [24,25]. To perform an effective cycling between the nodes, all of the nodes must be correctly synchronized [31,35]. If the time synchronization between the nodes isn't well designed, it can affect simultaneous transmission between the FD-nodes, causing propagation delays to increase.

Hidden and Exposed terminal issue. The hidden and exposed terminal issue usually arises in the contention based collision avoidance FD-MAC layer based protocols [30,34]. The hidden terminal problem occurs when a node cannot detect the transmission from one or more nodes during simultaneous transmission and instead sends its data to a node that is already receiving data from another node, resulting in collisions [30,35]. The exposed terminal problem occurs when one node overhears another node's transmission in order to prevent collisions [30,31].

Huge delays. Due to large propagation delays, handshaking-based FD-MAC protocols are severely hampered, lowering channel utilization rates [30,34]. The large propagation delays is the cause of relative propagation delays between the nodes, which is a serious challenge while designing of HS-FD-MAC protocols for underwater acoustic communication.

Power consumption. The FD-MAC protocols are designed to transmit data simultaneously, and they take a lot of energy to do so accurately [35]. Unexpected collisions during the transmission of data between the nodes also increase power consumption [35,37]. As a result, it is essential to develop FD-MAC protocols that can prevent collisions and save energy in a harsh underwater environment.

Noises. For all types of underwater FD-MAC protocols, noise is a common and fundamental problem [37,46,50]. There are two forms of noises: (a) noise produces by the human interference, such as machinery noise, shipping movement, cavitation (b) Ambient noise, such as hydrodynamics, biologics, seismic activates and so on. [50]. In order to counteract the noise, researchers have developed a variety of techniques. For instance, signal detection error correction coding and iterative (turbo) algorithms [46,68] have been established, resulting in improved UW channel efficiency, particularly in warm shallow water [46,68].

Attenuation. The transformation of acoustic energy into heat occurs during UWA wave transmission due to the increase in transmission range and frequency [50]. Low data rates and transmission bandwidths of a few kHz, as well as high communication frequencies, have a major effect on the acoustic signal and cause attenuation [30,46]. The rise in ocean depth, secreting, and echo production due to the irregular water surface and seabed are other factors that cause attenuation of the FD-UWA-MAC protocols signal [35].

Doppler spread/ Doppler shift. Doppler spread is caused by changes in water temperature, density, and salinity as a result of spatial-temporal differences in both deep and shallow water, reducing signal strength [46,50]. The existence of motion at the transmitter, receiver, and medium itself results in a huge Doppler shift in the frequency which further degrades the performance of high data rates, adjacent symbol interference, and generates ISI [46,50].

3.2. Contention-Free

The QoS of the UWA network is enhanced by congestion-free FD-MAC UWAC protocols, which have better channelization, bandwidth efficiency, and high resistivity against frequency selective fading [46]. However, it is unable to handle the high network load and collisions, resulting in low data rates. As a result, the FD contention-free MAC protocols

used various methodologies to protect the network from massive collisions, frequency selective fading, and improved transmission efficiency, and some of which are discussed below.

- **FDMA**. The FDMA based FD-MAC protocol provides an easy and straightforward means of channelization for usable bandwidth, but it is unable to manage the large number of UW nodes, resulting in poor bandwidth utilization and frequency selective fading issues, resulting in significant data loss [46].
- **CDMA**. A CDMA-based FD-MAC protocol has been tested, and it has two major advantages: bandwidth efficiency and the ability to effectively reduce frequency selective fading by using a full-duplex channel. However, it is also unable to protect the network from accidental collisions, which reduce data rate [46].
- **Hybrid-CDMA**. The hybrid CDMA based FD-MAC protocols, such as frequency hopping (FH-CDMA), direct sequence (DS-CDMA), and time hopping (TH-CDMA) have been proposed to address the issues raised by the FD-FDMA based protocols. It was discovered that the majority of these protocols used four HD Desert starRBS-1 modems for data transmission and reception to ensure FD communication. The FD-TH-CDMA MAC protocol can prevent collisions, while the FH-CDMA MAC protocol reduces frequency selective fading. We also discovered that certain hybrid MAC protocols provide hopping and substantial bandwidth benefits. Furthermore, the hybrid DS-CDMA and FDMA MAC protocol provides a medium for isolating two concurrently transmitting channels while maintaining FD communication. The FD-DS-CDMA, on the other hand, has some minor hardware problems. According to our findings, all of the above-mentioned protocols perform admirably; however, the FD-FH-CDMA outperforms the other FD-CDMA MAC protocols, particularly in the lack and bucket environments, with a near 90 percent success rate after three to four successful transmissions. Furthermore, it successfully mitigated multipath fading as well as frequency selective fading, resulting in high efficiency and low complexity [46].

3.3. Contention-Based

In contention based FD-UWAC protocols, users compete with one another for channel access to send their data. The user who wins the contention takes over the medium for a period of time, while the others remain silent and watch for a free channel. Contention based FD-MAC protocols are attractive due to their enhance throughput, energy efficiency, and robustness capabilities but these benefits are decline when network traffic load increases and results in huge data collision and energy consumptions [35,36]. To prevent contention-based FD-MAC protocols from these issues, advanced techniques, such as future scheduling (FS), interference cancellation, temporal and special reuse methods, IBFD properties, and FD-fixed time stamp handshakes, were introduced. As discussed below, contention based FD-MAC-UWAC protocols are divided into hand-shaking and random access protocols.

3.3.1. Hand-Shaking (HS)

- **BD-FD-MAC**. A BD-FD-MAC protocol successfully eliminate the issue of long propagation delays which take a long time to complete a successful transmission which effect the throughput efficiency of FD-MAC protocols [36]. Hence, the proposed BD-FD-MAC UWAC protocol increase the throughput significantly and reduced long propagation delays by shortening the time required for efficient data transmission. This protocol employs a back-off timer that works on the concept of prioritizing when and where to transmit. The sensor node (transmitter) is given the opportunity to transmit when the back-off timer expires. In order to prevent unwanted collisions with neighboring nodes, the sender often sends an identification message to the receiver node. The efficient data transmission begins after receiving the CTS from the destination node. The period of successful data delivery becomes miniature, which is helpful for throughputs improvement and for long propagation delay issue [36]. Physical and MAC header bits are 128 bits and 272 bits respectively, with a propagation delay of up

to 3.3 s, while this FD-protocol has a transmission speed of up to 710 bps. Although the BD-FD-MAC UWAC protocol yields significant results, it is implemented in a simulation environment, so it is necessary to implement this protocol in a practical environment, while energy efficiency is also needed to confirm the protocol's validity.

- **IBFD-MAC**. To fix issues such as power consumption, unexpected node collisions, long propagation delays, and low data rates, a novel IBFD-MAC protocol is proposed [35]. The link capacity is nearly doubled as a result of the IBFD approach implementation, and substantial data rates are achieved by reducing large end-to-end delays. Furthermore, by avoiding unwanted node collisions and reducing the long propagation delay, power consumption is decreased. In addition, as shown in Table 3, the following essential parameters are used in the implementation and testing of this proposed protocol in various water depths.

Table 3. Simulation parameters used by the HS-FD-MAC protocol.

Parameters	Values
Transmission range	500 m
Channel Bit rate	1000 bps
Bandwidth	10 Hz
Frequency range	12 kHz–22 kHz
RTS, CTS, ACK	64 bits
Data packets	1024 bits
Transmission power	8 Watt

- **DA-CSMA**. The DA-CSMA based protocol [30] is widely used in the development of the existing HS-FD-MAC layer protocols, for reducing the multipath effect, which results in the reduction of frequency selective fading [10,30]. The implemented DA-CSMA properties dramatically improved efficiency, by resolving the hidden and exposed terminal issue, as well as improving data collision elimination. This protocol is tested by implementing the FD-modem and splitting the channel into two portions for simultaneous transmission of control and data packets, reducing collisions [30], and achieving high throughput while consuming little energy. It will be important in the future to verify its robustness using a wide network, while it is implemented for 10 nodes randomly distributed in a square km underwater environment. Table 4 displays the key parameters used in the implementation of this protocol.

Table 4. Simulation parameters taken by the FD-DA-CSMA protocol.

Parameters	Values
RTS/CTS	**64 bits**
Data Packets	1024 bits
Transmission rate	500 bps
Propagation range	0.5 km
Power consumption	
At transmission	10 W
At reception	80 mW
Control packets	
Modulation/Demodulation	DSSS
Frequency	6–8 kHz
Data Packets	
Modulation/Demodulation	OFDM
Frequency	4–6 Hz
Success Rate	95%

The DA-CSMA UWAC protocol is compared to the traditional HD-CSMA-UWAC protocol, as shown in Figure 4. The DA-CSMA protocol outperforms conventional HD-CSMA by providing higher throughputs, lower energy consumption, exhibiting low end-to-end delays under heavy network load.
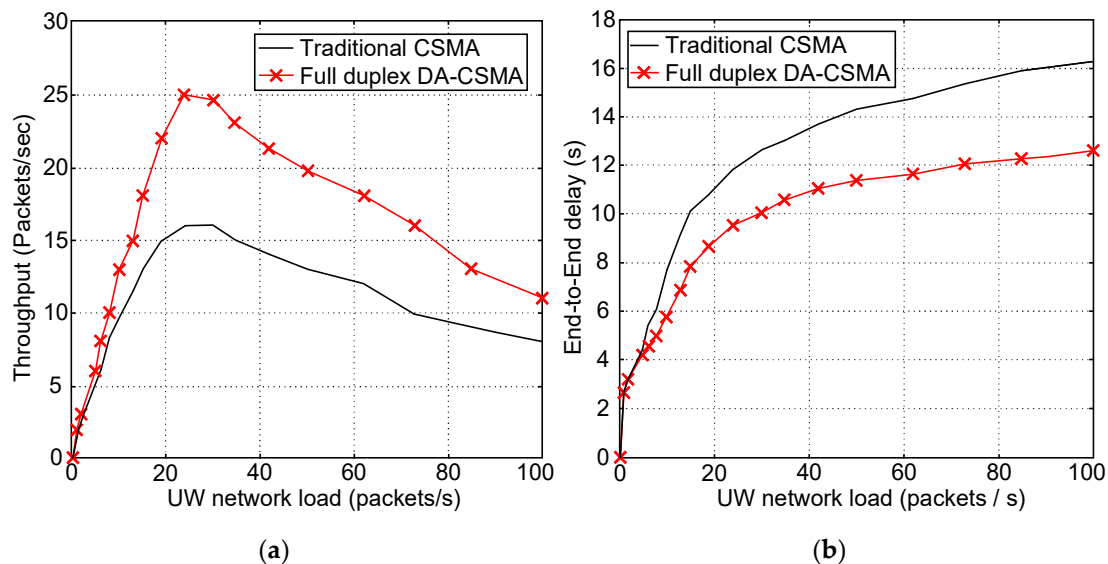

(**a**)   (**b**)

Figure 4. (**a**) Throughput and (**b**) end-to-end delay comparison of full-duplex DA-CSMA and traditional CSMA MAC protocols.

- **FS-MACA**. The FD FS-MACA protocol [37], based on the future scheduling (FS) hand-shaking (HS) mechanism scheme, is proposed as a new handshaking protocol [37]. The HS scheme ensures data transmission by scheduled procedures and future negotiations between the sender and receiving segment. The physical channel is divided into two parts, one for real data transmission and the other for control packet negotiation, resulting in higher throughput and less interference while achieving FD communication. This protocol was tested in a network of 100 unsystematically distributed nodes in an underwater environment with a 2×2 square km of surface area, and it achieved a data rate of 100 kbps with packet lengths ranging from 400 to 1000 bytes. Despite the fact that the mentioned protocol above is capable of managing high traffic loads while preventing collisions without the use of time synchronization or ACK, there are still open issues that need to be addressed. Since it does not use time synchronization, this protocol is unable to manage long propagation delays and experiences severe throughput degradation; however, this may be an important topic for future study.

- **FDCA-MAC**. The FDCA-MAC UWAC protocol [34] is based on the idea of transmitting and receiving on the same frequency at the same time, reducing hidden and exposed terminal problems and allowing FD-UWAC modems to achieve high throughput. Recent research shows that using FD underwater acoustic modems, the SI effect can be cancelled easily [11,29,33], i.e., the HS mechanism can be used to predict transmission scheduling by passively receiving local information about neighboring node propagation delays. The proposed protocol is based on this concept, and it achieves large throughputs [34]. Furthermore, FD modems are used to implement multiple HS with their neighbors and to increase throughputs while achieving temporal and spatial reuse. It will be necessary to test its success in both a lack and a sea environment in the future.

- **TFH-MAC**. A novel TFH-MAC protocol is proposed, which significantly reduces the SLI issue, which is a common problem with FD UWAC systems, while achieving FD communication [69]. The TFH-MAC protocol is implemented on a node that acts as a centralized node among multiple nodes. The centralized node connects the

multiple nodes, using the TFH-MAC protocol to ensure that communication between the nodes is secure. The TFH-MAC protocol significantly reduces SLI, allowing for higher throughput while using less power. However, we discovered that this protocol is unable to cope with long propagation delays, resulting in reduced performance when used in a large network.

As shown in Figure 5, we compare the throughputs of various HS-FD-MAC layered-based protocols [35,36]. The IBFD-MAC protocol [35] outperformed the full-duplex FS-MACA and HS-HD-MACA protocols [21] by demonstrating a substantial throughput gain.

- **E-FD-MAC**. An enhanced E-FD-MAC protocol is proposed in [38], that allows the FD channel to simultaneously exchange data packets in a minimum possible time, as shown in Figure 6. This protocol allows the source and destination to exchange data using sensed information without being affected by unexpected collisions, which greatly increases throughput and reduces propagation delays. Due to its ability to transmit and receive control and data packets, the proposed E-FD-MAC receives active transmissions earlier than the current HD-MAC protocol. The way it works is shown in Figure 6. The UW sensor nodes detect the data and set a back-off timer based on the transmission priority. When the back-off timer on underwater sensor nodes expires, a transmission opportunity to the target destination node becomes open. In order to transmit information to the target destination node, the source node that acquires the transmission opportunity broadcasts an RTS to neighbor nodes that includes the target node's ID. After receiving RTS, the destination node sends a clear-to-send (CTS) message to the source node, instructing it to conduct FD communication. After receiving the CTS, the source node and the destination node send the sensed data to each other in the order specified in the transmission order.
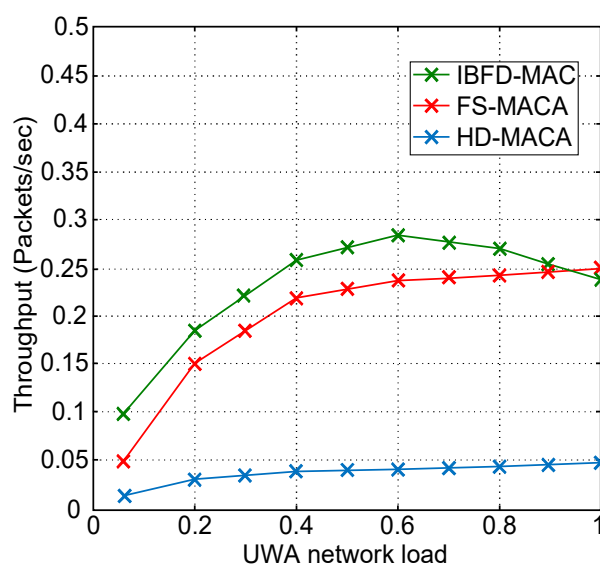

Figure 5. Throughput comparison of FS-MACA, HD-MACA and IBFD-MAC protocols.

3.3.2. Random Access-Based

Random access MAC protocols are designed to send and receive data between multiple nodes by using the medium randomly without any control or HS mechanism. This increases the likelihood of high collisions and massive energy consumption [70]. Researchers developed a new FD-random access based MAC protocol for multi-hop ad-hoc networks to address this problem, as discussed below.
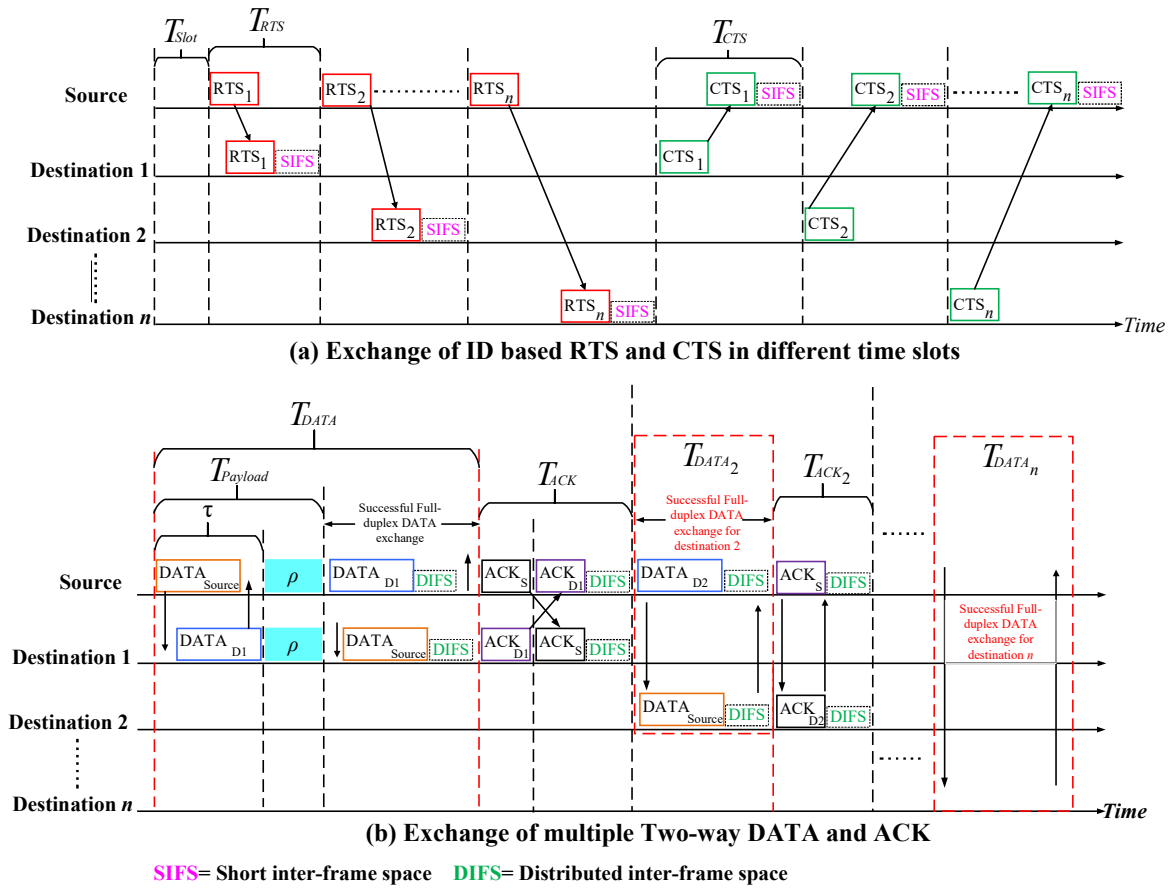
(a) Exchange of ID based RTS and CTS in different time slots

(b) Exchange of multiple Two-way DATA and ACK

SIFS= Short inter-frame space   **DIFS**= Distributed inter-frame space

Figure 6. Simultaneous transmission of control and data packets though E-FD-MAC.

- **FDCP-MAC**. A self-organized FDCP-MAC protocol for multi-hop ad-hoc UWAN network has been presented in [39]. It has the ability to utilize the channel and avoid huge collision more efficiently at high network load with the help of fixed time HS and time stamped conflict resolution mechanism. This system randomly generate the data packets to random destination and all the sending nodes are completely aware of the all the static destination of the which are randomly distributed in the UW environment. This FDCP-MAC achieves enhanced throughput and lowest rate of collisions [39] as compared to the conventional HD-MAC protocols [7,71].

3.4. Comparative Analysis of MAC Layer-Based UWAC Full-Duplex Protocols

As shown in Table 5, we compare various MAC layered FD-UWAC protocols in this section. We compare the technologies used in various FD-MAC-UWAC protocols, as well as the implementation of these FD protocols in various environments, and their performances with respect to various metrics such as throughput, delay efficiency, energy efficiency, and transmission range. We found that FD-MAC-UWAC protocols outperformed in terms of collision avoidance, resolving the hidden and exposed terminal problem, and achieving higher throughputs and energy efficiency, etc. The performance comparison is explained below.

Table 5. Comparison of various FD-MAC layer-based UWAC protocols.

Protocol Type	Name/Ref.	Network Type	Implementation	Performance Matrices				
				Throughput	Delay Efficiency	Energy Efficiency	Transmission Range	Data Rate
Contention-free	CDMA [46]	Ad hoc	Shallow water	Low	Low	Moderate	15 feet	NA
	Hybrid CDMA [46]	Ad hoc	Shallow water	Moderate	Low	Moderate	15 feet	NA
	FH-CDMA [46]	Ad hoc	Shallow water	High	Low	Moderate	15 feet	NA
Hand –Shaking	BD-FD-MAC [36]	Single hop	Simulation	High	High	Enhanced	NA	NA
	IBFD-MAC [35]	NA	simulation	Medium	Low	Moderate	Very Low	Moderate
	DA-CSMA [30]	Ad hoc	Shallow water	High	High	Low	Low	Low
	FS-MACA [37]	distributed Ad hoc network	simulation	Medium	Moderate	Very Low	High	High
	FDCA-MAC [34]	Single hop / Multi-hop	SEA-Swarm network	Moderate	Moderate	Enhanced	Moderate	Very Low
	TFH-MAC [69]	NA	Simulation	High	Very Low	Enhanced	NA	NA
	E-FD-MAC [38]	Single hop	Simulation	High	High	Enhanced	NA	NA
Random Access	FDCP-MAC [39]	Multi-hop Ad hoc	Simulation	Low	Moderate	Moderate	Very High	High

3.4.1. Throughput

In the realm of contention-free protocols, the FD-FH-CDMA technique outperforms the simple FD-CDMA technique because it effectively mitigates multipath fading and frequency selective fading, resulting in high throughput. Thanks to FDMA's ability to isolate the channel and perform error-free simultaneous communication [46], the combination of FDMA and hybrid CSMA also performs better. The BD-FD-MAC [36] protocol is a single hop network with DCF and back-off timer communication features, which helps to reduce unexpected delays and shorten the time it takes for data to be successfully transmitted. The BD-FD-MAC achieves a high throughput curve as the number of UW sensor nodes grows in size. The IBFD-MAC [35] protocol uses receive and forward technique to improve data rate and throughput. However, due to the presence of the SI effect, as the net-work load increases, the throughput gradually decreases. In comparison to FS-MACA [37], its efficiency is similar due to the future scheduling technique, but FC-MACA maintains a consistent high throughput under heavy traffic. In the future, a successful SI cancellation technique can improve IBFD-throughput MAC's even more. To prevent unintended collisions, the FD-DA-CSMA [30] uses two different channels to send and receive control and data packets at the same time, resulting in higher throughput. FDCA-MAC [34] creates a collision-free map that can determine if the current communication channel conditions are suitable for collision-free transmission. Throughput rises by 30% and 60% in single hope and multi-hop network tests, respectively. Two and fold is another advanced technique for the construction of FD communication operation in the TFH-MAC protocol [69] for increasing throughput. In addition, the IBFD communication method has been implemented to remove the self-loop and SI in FD communication, thereby improving throughputs gain. The E-FD-MAC [38] protocol is tested on a single hop network that uses Short Inter-Frame Space (SIFS) and back-off timer-based communication capabilities to minimize unexpected delays and speed up data transmission. The E-FD-MAC [38] achieves a high throughput curve as the number of UW sensor nodes grows in size using this method. FD-fixed time stamp hand-shake and time-stamp based dispute resolution are two revolutionary strategies used in random access based FDCP-MAC [39] to improve the protocol's throughput and reliability. Even with a high network load, these techniques maintain efficiency.

3.4.2. Delay Efficiency

To decrease unexpected collisions and delays, FD channel was used in FD-CDMA-based protocols [46]. However, the FD channel is not the most successful way to tackle long propagation delays in UWAC networks. Future research in this field is still possible. The BD-FD-MAC [36] protocol, in which source nodes send ID-based RTS control packets to the destination node, increases the successful transmission time and effectively reduces delays. The FD-DA-CSMA [30] architecture effectively resolves collisions between the control to control and control to data packets through two different channels, resulting in low end-to-end delays. To prevent accidental collisions and significant propagation delays, the FS-MACA [37] uses the future scheduling (FS) technique to allow future agreements between the transmitter and receiver for successful transmission. However, this FS technique is incapable of effectively dealing with long propagation delays, and time synchronization remains a problem. To reduce the significant propagation delay between its neighbor nodes, FDCA-MAC [34] uses a full-duplex communication channel. The end-to-end delay between the UW nodes of the TFH-MAC protocol [69] increases drastically as the network load increases. The control and data packets in the E-FD-MAC [38] protocol are ID-based, which automatically prevents unexpected collisions and improves delay performance, while in the FDCP-MAC protocol [39], time stamp-based dispute resolution reduces the collision rate by a factor of 3 to 4.

3.4.3. Energy Efficiency

Pulse position coding reduces energy consumption in FD-CDMA-based protocols [46] by providing a special window of fixed length in which each of the data pings must

occur. The BD-FD-MAC [36] protocol sends and receives ID-based control and data signals, which eliminates unwanted collisions and reduces the power consumption of UW sensor nodes. Transmission of ACK/NACK control packets in conventional MAC protocols takes a long time to propagate and consumes a high power. To solve this issue, IBFD-MAC [35] does not send any ACK packets to any active transmission and instead executes it correctly. If the transmission fails, the NACK packet is returned to the sender for retransmission by the IBFD-MAC. This approach saves lots of power. Unexpected collisions, hidden and exposed terminal issues increase power consumption between UW nodes in any MAC protocol, which FD-DA-CSMA [30] efficiently solves. For transmission, the system uses 10 W, and for reception, it uses 80 mW. FS-MACA [37] also uses two different channels for simultaneous transmission of control and data packets, as well as potential scheduling to prevent collisions, resulting in a more energy-efficient system. The FDCA-MAC [34] estimates average power consumption using the Sea Swarm network, which consumes considerably less power due to its collision avoidance algorithm. The TFH-MAC [69] is a highly efficient technique that continuously lowers power consumption as network load increases. The E-FD-MAC protocol [38], which is based on ID, effectively increases throughput and delays by using the FD communication channel to minimize power consumption. Although the FDCP-MAC protocol [39] is designed to reduce collision rates, collisions still occur as the network load increases, implying that it is possible to save a significant amount of energy on UW nodes.

3.4.4. Transmission Range

In the shallow water region, the FD-CDMA-based protocols [46] provide the shortest transmission range of only 15 feet between full-duplex modems, pointing this area further investigation. To pass 1000 bps, the IBFD-MAC protocol [35] archives the lowest transmission range of 500 m at various water depths. In the Yellow Sea near northeastern China, the maximum transmission range of FD-DA-CSMA [30] is up to 0.5 km. However, the protocol's efficiency for new and drop nodes, as well as its implementation in a large UWAC network, must be checked. UW nodes centered on FS-MACA [37] archive 2 square kilometers of highest transmission range to transmit 100 kbps data. The transmission range of FDCA-MAC [34] ranges from 500 to 1000 m. The fact that the rise in data rate is proportional to the increase in transmission range is intriguing. The FDCP-MAC protocol [39] achieves a 3 km transmission range with a 2400 bps data rate.

4. Suggested Cross-Layered Design Architecture Using Full-Duplex Physical and MAC-Layered UWAC Systems

Underwater sensor networks (UWSNs) are typically made up of a variety of sensors that communicate using various protocols in order to estimate underwater activities in shallow or deep water and create a fast communication channel. The cross layer architecture can be used to deploy various FD communication based UWSNs in the ocean environment, as shown in Figure 7. The cross-layer protocol architecture allows for the efficiency of underwater acoustic networks to be optimized. It eliminates the conventional constraint that information can only be transferred between two adjacent layers, while information can be exchanged between non-adjacent layers.

The PHY layer provides information about estimated SNR to the MAC layer, which assists the MAC layer in resetting the back-off timer for retransmission, resulting in energy savings and reduced network end-to-end latency. The UWSNs can function via terrestrial base stations, satellites, and floating buoys, as shown in Figure 7. Using efficient energy utilization and joint optimization of their functionalities at different layers of the protocols stack, the cross-layered architecture can provide a roadmap to higher network throughputs [72–74]. The described design focuses on energy efficiency [74–76], as energy consumption is a major concern in UWSNs, and underwater sensors are usually powered by batteries [72]. Unexpected collisions consume more battery power, resulting in greater interference in UWSNs [35]. Traditional CSMA/CA hand-shaking-based MAC protocols can effectively mitigate this issue, but they waste a lot of energy during handshaking and

retransmission of control packets. The IBFD UWASNs minimize the number of control packets, resulting in increased battery performance and energy savings.
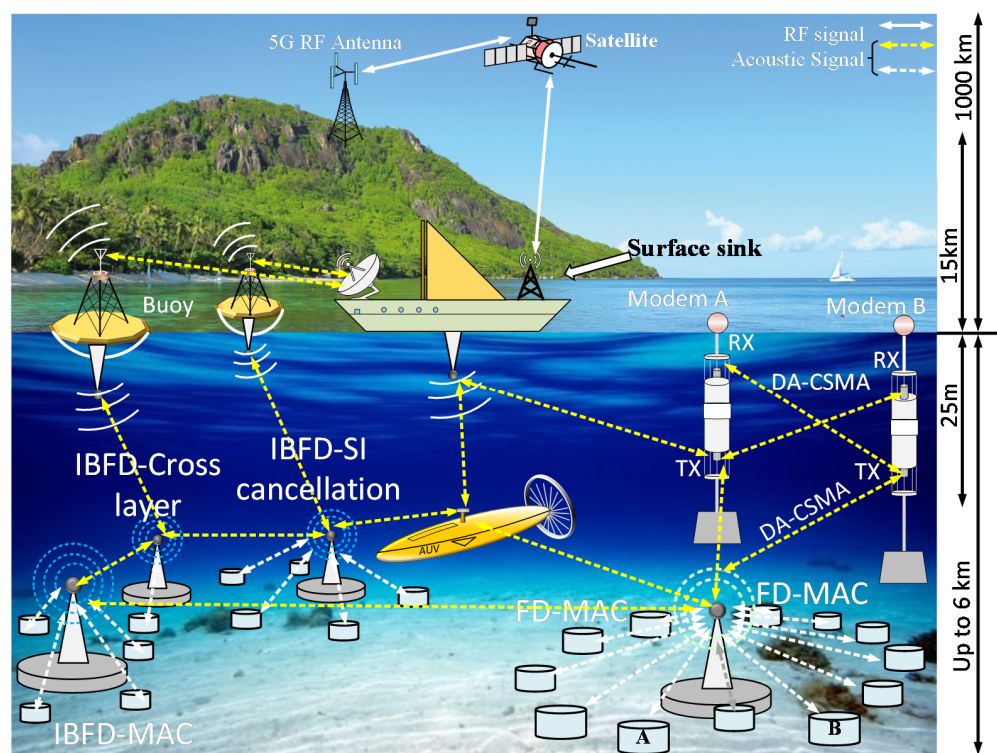

Figure 7. Various FD-PHY and MAC-based UWASNs in a cross-layered perspective.

A centralized network structure is also considered in Figure 7, where the data link layer considers the MAC layer algorithm and applies a cross-layer protocol architecture approach between the physical layer and the MAC layer. Via channel information input from the physical layer, the data link layer can more effectively distribute channel resources, resulting in increased channel resource usage and power savings. At the same time, the physical layer will boost communication quality by responding to data link layer power adjustment and control commands. This cross-layer design will reduce power consumption, reduce propagation delay, and increase throughput. Furthermore, further optimization of IBFD with PHY and MAC layers in a cross-layered perspective may be possible in the future [35].

Furthermore, an optimized cross-layer based on the HD CSMA/CA protocol [72] that does not use the RTS/CTS handshake for channel reservation can be implemented. However, it employs a virtual listening system to assess if the channel is busy or ideal for data transmission by listening to data frames from other nodes. The approximate SNR information provided by the PHY layer aids the MAC layer in resetting the back-off timer for retransmission. This will save resources while also reducing network end-to-end latency and increasing throughput.

5. Conclusions and Future Research Directions

5.1. Conclusions

An extensive review of different FD-physical layered systems and MAC layered protocols is carried out. Physical layered FD systems are mainly OFDM-based, digital modulation-based and spread spectrum-based. The FD MAC layered protocols are categorized as contention-free and contention-based. Contention-free protocols include CDMA, FDMA, and hybrid CDMA, while contention-based protocols are divided into two types: HS and RA. Physical and MAC FD-UWAC systems and protocols are affected by various

challenges, according to the review. Different FD physical and MAC FD-UWAC systems and protocols are compared based on various metrics, as well as their implementation, benefits, and drawbacks in various environments.

In the following section, we discuss various open research problems in these FD-physical layered and MAC layered protocols, as well as potential research directions. We pointed out that this field of research is still in its early stages and needs to be further developed.

5.2. Future Directions

The FD-UWAC physical layered systems, as well as MAC layered protocols, operate in a dynamic and challenging underwater environment. When going over the FD, we discussed the advantages and disadvantages of physical layered systems and MAC protocols, and we suggested potential future directions in this section.

Physical layered FD-UWAC systems are mostly based on OFDM, as we pointed out. These OFDM-based FD systems outperformed in terms of low ISI, ICI, and transmission latency reduction [19,40]. However, further research is required to improve the power efficiency of these FD systems as well as to reduce the hardware complexity. To make maximum use of available bandwidth, OFDM-based IBFD-UWAC systems have been widely implemented [23–25,41]. They have achieved fast convergence speed, high precision, high robustness, high numerical stability, and low computational complexity. In addition, these FD systems are typically used to inhibit SI effects such as optical SI, analog SI, SLI, multiple reflection interference, and ISI [22–24,41]. These FD systems, on the other hand, also need to increase their overall system throughputs as well as spectral performance, and they must do so while using limited bandwidth. Furthermore, these FD- systems need improvements in ambient noise cancellation and hardware reliability. The FSK-FD-UWAC systems protocols were developed to build a long-range communication link between UWAC robots, achieving high data rates while conserving energy, and have been implemented for off-shore oil productions [29]. However, these FD-systems need improvements in robustness and multipath interference cancellation, as well as a reduction in hardware complexity [29], which could be very promising directions for future study.

We discovered that the FD-MAC protocols worked well, significantly reduced collision, resolved the hidden and exposed terminal problem, and had higher throughputs and energy efficiencies. These protocols, on the other hand, face a number of problems, which are illustrated and potential directions are proposed accordingly. While implementing in an ad-hoc UWAC system [39], a self-organized HS-FD-MAC protocol successfully eliminated unwanted collisions, demonstrated better channel utilization in high network load, and exhibited high throughput benefit. However, a power efficiency study is needed to confirm the protocol's validity. The HS-FD-DA-UWAC protocols in [30], demonstrated improved performance by resolving the hidden and exposed terminal issue, as well as high overall and energy efficiency. On the other hand, it is recommended that this protocol be checked for new and drop nodes, as well as its implementation in a large UWAC network. Furthermore, this protocol demonstrated a low data rate, which is also a problem. In [37], the proposed HS-FS-MACA protocol, which showed a major improvement in collision avoidance, high throughput, and improved channel bandwidth. However, this protocol is incapable of dealing with long propagation delays, and time synchronization remains an issue. The HS-FDCP protocol proposed in [39], increased throughput by demonstrating substantial collision avoidance at the transmitter and receiver ends, as well as improved network throughputs, channel utilization, and temporal and spatial reuse. However, this protocol consumes more energy and has low robustness, and its practical implementation is also needed, leaving an open research question. The HS-IBFD-MAC UWAC protocol used twice the connection capacity, effectively reducing high node collisions and long propagation delays while consuming less power [35]. However, SI cancellation and the multipath effect are not taken into account in this protocol. This protocol may also be expanded to include cross-layered architecture. When implementing for a heavy load traffic network, the HS-FD-MAC UWAC protocol proposed in [69] significantly reduced

SLI, improved throughput, and reduced power consumption. However, due to the long propagation delays, this protocol is ineffective.

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Conflicts of Interest: It is declared that authors have no conflict of interest.

Nomenclature

AUA-CCS	Asynchronous Underwater Acoustic Cooperative Communication Systems
A-DTWRS	Asynchronous Diamond Two-Way Relay System
A-IBFD	Asynchronous In-Band Full-duplex
ASIC	Adaptive Self-Interference Cancellation
ARQ	Automatic Repeat reQuest
AF-OFDM	Amplify and Forward Orthogonal Frequency Division Multiplexing
ACD	Analog to Digital Conversion
ASCII	American Standard Code for Information Interchange
ACK	Acknowledgment
ANE	Adaptive non-equalizer
BD-FD-MAC	Bi-Directional Full-Duplex Medium Access Control
BER	Bit Error Rate
CP	Cyclic Prefix
CSK	Code Shift Keying
CUAC	Cooperative Underwater Acoustics Communication
Cooperative-OFDM	Cooperative Orthogonal Frequency Division Multiplexing
CDMA	Code Division Multiple Access
CST	Clear-to-Send
DS-CDMA	Direct sequence Code Division Multiple Access
DS-CDMA	Direct sequence Code Division Multiple Access
DA-CSMA	Distance Aware Carrier Sense Multiple Access
DSSS	Direct Sequence Spread Spectrum
DSD	Dichotomous Coordinate Decent
E-FD-MAC	Enhanced Full-Duplex MAC
FD	Full-Duplex
FH	Frequency Hopping
FD-DSIC	Full-Duplex Digital Self-Interference Cancellation
FD-SS	Full-Duplex Spectrum Sensing
FSK-UWAC	Frequency Shift Keying Underwater Acoustic Communication
FSK	Frequency Shift Keying
FPGA	Field Programmable Gate Array
FDMA	Frequency Division Multiple Access
FH-CDMA	Frequency Hopping Code Division Multiple Access
FD-CDMA	Full-Duplex Code Division Multiplexing

FD-MAC	Full-Duplex Medium access Control
FS-MACA	Future Scheduling Multiple Access with Collision Avoidance
FDCA-MAC	Full-Duplex Collision avoidance Medium Access Control
FDCP-MAC	Full-Duplex Collision avoidance Protocol Medium Access Control
HS	Hand-Shaking
HD	Half-Duplex
HSIC	Hybrid Self-Interference Cancellation
IBFD	In-Band Full-Duplex
IBFD-MAC	In-Band Full-duplex Medium access control
IBFD-UWAC	In-Band Full-Duplex Underwater Acoustic communication
IFFT	Inverse Fast Fourier Transform
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
IUI	Inter User Interference
IoUWT	Internet of Underwater Things
LDP	Low Detect Probability
LNA	Low Noise Amplifier
LTI	Local Transmission Interference
LEI	Local Emission Interference
MAC	Medium Access Control
ML	Maximum Likelihood
ML-SC-IBFD	Maximum Likelihood Sparse Constraint In-Band Full-Duplex
MSE	Mean Square Error
MUAC	Multi-User Acoustic Communication
NPML	Non-Parametric-Maximum-likelihood
NLMS	Normalized Least Mean Square
NACK	Non-Acknowledgement
OFDM	Orthogonal Frequency Division Multiplexing
OFDM-IBFD	Orthogonal Frequency Division Multiplexing In-Band Full-duplex
OPRLS	Over-Parameterization based Recursive Least Squares
PRP	Pairwise Error Probability
PPM	Pulse position modulation
PAPR	Peak-to-Average-Power Ratio
PVDF	Poly Vinylidene Fluoride
QoS	Quality of Services
RA	Random Access
RSI	Residual Self-Interference
RLS	Recursive Least-Square
RST	Request-to-Send
SIR	Signal-to-Interference-Ratio
SI	Self-Interference
SIC	Self-Interference Cancellation
SS	Spread Spectrum
SS	Spectrum Sensing
SLI	Self-Loop Interference
SDFE	Soft-Decision Feedback Turbo Equalization
SNR	Signal-to-Noise Ratio
TH	Time Hopping
TDMA	Time Division Multiplexing
TRDC	Time Reversal Digital Cancellation
TH-CDMA	Time Hopping Code Division Multiple access
TFH-MAC	Two and fold hand-shaking medium access control
UWAC	Underwater Acoustic Communication

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