On Reliable Data Transfer in Underwater Acoustic Networks: A Survey From Networking Perspective

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***Abstract*—Reliable data transfer aims to guarantee that the destination node can successfully receive what have been sent to it, and the basic mechanisms extensively for this purpose in radio frequency (RF) networks include redundancy and retransmission. However, this issue becomes much more challenging in underwater acoustic (UWA) networks in comparison with RF networks due to the following peculiar features of UWA channels: poor quality and high dynamics of UWA channels, much smaller channel capacity and much larger propagation delay, as well as asymmetric connectivity of UWA links. These features either limit extensive application of redundancy mechanisms or influence the performance of retransmission mechanisms. Therefore, many research results have been reported in the literature, with several different design strategies and various proposals available. This paper conducts a survey on many schemes proposed from the data link layer to the transport layer, and discusses challenging issues necessary for further research.**

***Index Terms*—Reliable data transfer, underwater acoustic network (UWAN), underwater acoustic channel, redundancy, retransmission.**

I. INTRODUCTION

RELIABLE data transfer attempts to guarantee that the destination node can successfully receive what has been sent to it, and is the basis of many underwater applications related to tactical surveillance, coastline defense, off-shore production, ecological monitoring and scientific exploration as well as disaster prevention etc. For examples, reliable data transfer between a mother ship and an unmanned underwater vehicle (UUV) for mine or submarine detection is necessary for successful data collection and UUV control. An undersea command, control, communications and navigation (C3N) infrastructure can be build up on top of reliable wireless acoustic connections between distributed undersea nodes. Off-shore oil production may pollute marine environments due to oil leaking, and robust monitoring with reliable data transfer from underwater sensors to the surface center should be in place. In tsunami detection, alarm messages must be delivered to all relevant destinations in the area successfully and timely.

The primary events leading to data reception failure include low channel quality due to interference and signal fading leading to reception error, congestion causing data loss, and collision leading to data corruption as well as network attacks affecting the normal data forwarding operation. Network attacks fall in the scope of network security and will not be discussed in this paper, and a separate survey needs to be conducted.

In radio-frequency (RF) based wireless networks, the typical techniques to provide reliable data transfer over unreliable networks include redundancy and retransmission mechanisms. The redundancy mechanism aims to provide the receiver with error detection and correction capabilities, while retransmission attempts to improve successful reception probability at the receiver even with transfer reliability guarantee. A typical redundancy mechanism is Forward Error Control (FEC), which however alone cannot always guarantee transfer reliability, depending on channel quality often measured in terms of bit error rate (BER). If the BER of a channel is too large for the receiver to correct all errors, retransmitting the related data should be triggered for successful reception. A typical retransmission mechanism is Automatic Repeat Request (ARQ), which jointly uses acknowledgement schemes at the receiver to update the sender of the reception status and timing schemes at the transmitter. More discussion on this part can be found in Section II.

The challenges facing underwater acoustic networks (UWANs) [1] for reliable data transfer stem from the following aspects. i) The underwater acoustic (UWA) channel is characterized by poor quality and high dynamics due to time-varying propagation conditions, multipath propagation, fading as well as motion-induced Doppler distortion and spread, which result in high BER [2]. ii) UWA channels are inherently wideband as the bandwidth occupied by the signal is not small compared to its center frequency, leading to the existing narrowband channel models inappropriate [3], [4]. iii) The small UWA channel capacity limits wide application of redundancy mechanisms. iv) The long propagation delay due to slow acoustic wave speed (e.g., 1.5 km/s in seawater) makes ARQ schemes very inefficient. Furthermore, UWA links may be asymmetric, which affects establishment of a feedback channel required by ARQ. Meanwhile, the following technological facts make reliable transfer scheme design more difficult: most available UWA modems can operate only in half-duplex mode, and consume large amount of energy for both transmission and reception, while underwater network nodes are often battery-operated [5].

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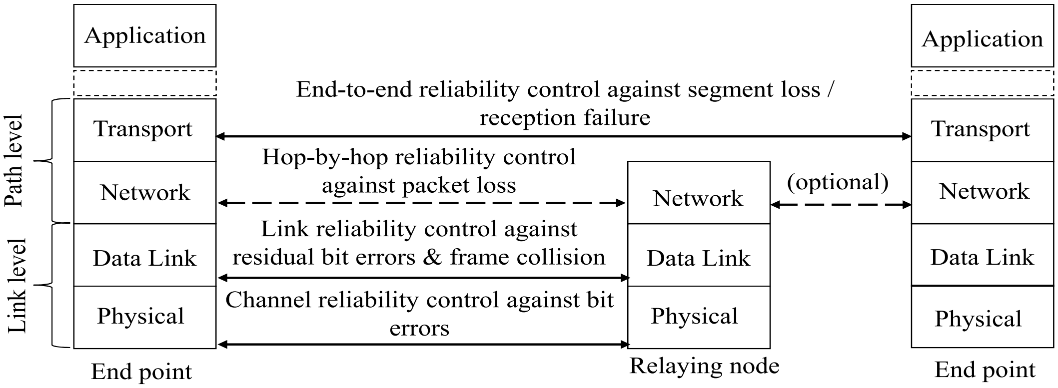

Fig. 1. A general architecture for end-to-end transfer reliability control.

More description on UWA communication can be found in Section III-A.

To deal with the peculiar features of UWANs mentioned above, many schemes have been proposed as reported in [1], using different design strategies such as cross-layer design and hybrid design as well as various types of mechanisms. Typically, these schemes attempt to improve the performance of simple ARQ schemes suitable for half-duplex links such as packet train [6], or make sophisticate ARQ schemes suitable for UWA channels by creating full-duplex UWA links. Meanwhile, various coding schemes such as erasure codes [7] and network coding [8], [9] are extensively used to improve the performance of reliable transfer schemes. Several other schemes such as multi-path transmission, power control and cooperative transmission have also been jointly used with either FEC or ARQ for transfer reliability control. Note that, other networking techniques such as medium access control (MAC) and routing are usually handled by one layer, e.g., MAC by the data link layer while routing by the network layer, although cross-layer design may be used jointly to further improve their performance. Differently, end-to-end data transfer reliability control involves the physical layer up to the transport layer. However, this feature has not been highlighted in the literature.

This paper conducts a survey on reliable data transfer schemes for UWANs reported in the literature, mainly focusing on networking technologies on the data link layer, the network layer and the transport layer. A brief discussion is also provided on several channel control schemes on the physical layer for channel quality and capacity improvement related to reliable transmissions. However, a comprehensive investigation on this part is out the scope of this paper, and the reader can refer to the relevant surveys such as [10] and [11] for more details.

The remainder of this paper is organized as follows: Section II gives an overview of the fundamentals for reliable data transfer, including architecture, FEC and ARQ. Section III briefly discusses several control schemes of UWA channel quality that can benefit FEC schemes. Sections IV–VI review reliable transfer schemes proposed respectively for the data link layer, the network layer and the transport layer. A comprehensive discussion on the reviewed schemes is conducted in Section VII, highlighting remaining issues necessarily to be further addressed. The paper is concluded in Section VIII.

II. FUNDAMENTAL COMPONENTS OF RELIABLE TRANSFER

This section briefly reviews the architecture and typical error control schemes used to provide reliable data transfer.

A. Architecture for Reliable Transfer

The main functionalities used to support reliable transfer are usually distributed into the lower four layers of the open system interconnection (OSI) model, and can be grouped into two levels: link level and path level, as illustrated in Fig. 1.[1] The link-level functions attempt to provide reliable transmission over links between neighboring nodes, mainly combating transmission errors caused by noises and interferences as well as frame collision. The path-level functions aim to provide end-to-end reliable transfer over paths across the network, mainly dealing with losses of packets occurring during their journeys to their destinations.

The link-level functions are distributed on the physical-layer and data link layer (DLL). The physical layer functions are used for channel quality and error controls. The first part attempts to improve channel capacity against various factors deteriorating channel quality, using modulation/demodulation and interference alignment [12], and exploiting transmit diversity gains via smart antenna (e.g., [13]) and Multiple-Input-Multiple-Output (MIMO) technologies [14]. The second part mainly applies channel coding to enable the receiver to correct errors in order to minimize reception errors, typically with FEC schemes. However, it is difficult and not cost-effective for the physical layer to guarantee error-free reception. Thus, the DLL, particularly the logical link control sub-layer, applies ARQ to remedy this part for error-free reception over the physical link via retransmission. ARQ can also be used to recover collided frames occurring on this layer.

The path-level functions include hop-by-hop reliability control on the network layer and end-to-end reliability control on the transport layer. When error-free packets travel across the network, they may experience congestion, leading to packet loss. In this case, a hop-by-hop retransmission of the lost

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[1] To simplify discussion henceforth, “packet” is used as a general protocol unit to refer to either the frame of the data link layer, the packet of the network layer or the segment of the transport layer.

packets can be performed with a similar ARQ scheme as mentioned above, i.e., the upstream node of the link retransmits the packets lost at the downstream node. However, such kind of implementation complicates the network node. In practice, the hop-by-hop reliability control may not be adopted if an end-to-end reliability control is in place, which actually is adopted by the TCP/IP network. With an end-to-end transmission reliability control (e.g., TCP), an ARQ scheme is performed between a source-destination pair without involving any relaying nodes (e.g., routers). That is, the source node keeps retransmitting a packet until it has received a positive acknowledgement on the sent packet, subject to a maximum number of retransmissions. Note that, it is not necessary for an end-to-end reliability control scheme to assume the availability of any reliability control schemes on the lower layers. Particularly in the TCP/IP network, TCP performs both transmission reliability control and congestion control, which makes the IP layer very simple and robust.

B. Typical Error Control Schemes

The typical schemes include FEC and ARQ, which are mainly different in terms of who (either the sender or the receiver) is responsible for error correction as illustrated in Fig. 2.

1) FEC: With FEC, it is the receiver who corrects errors based on the received redundancy from the sender to minimize bit errors in communication process. Erasure codes [7] are FEC codes used in binary erasure channels, where transmitted data may disappear, while wireless communication channels are typically erasure channels. Such kind of codes can be performed on bit level or packet level. Bit-level erasure codes for bit-level FEC are often used for channel coding [15], which uses redundant bits to detect and correct bit errors of received signals. Several linear coding schemes, for which any linear combination of codewords is still a codeword, are used for this type of FEC, such as repetition codes, Hamming codes, Bose-Ray-Chaudhuri-Hocquenghem (BCH), Reed-Solomon (RS) and low-density parity-check codes (LDPC) etc. These linear coding schemes can be used to design more efficient encoding and decoding algorithms than other coding schemes. Among them, the repetition code is the simplest one, with which, for 1-bit original information, multiple redundant bits will be transmitted together along with the original bit in order to increase its successful reception probability. The more redundant bits are transmitted, the higher successful reception probability of the original bits will be. However, redundant transmission consumes more bandwidth and more energy. Another typical bit-level FEC is convolutional codes such as Viterbi code, which is computational complex and undesirable for battery-operated underwater nodes. More reading on channel coding can be found in [16].

Packet-level erasure codes for packet-level FEC also use redundancy to support reliable data transfer over lossy paths. Such schemes encode a message of k packets into a set of longer encoded messages each with n packets such that the original message can be recovered from a subset of the encoded messages. One class of such schemes requires a constant code rate $\frac{k}{n}$, such as Tornado codes [17], which however is not suitable for highly dynamic channels. Another type of such scheme, called rateless codes [18], releases such constraint as described below. There is no theoretical limit to the number of encoding packets to be transmitted as redundancy to the receiver, and the encoded packets can be sent as many as necessary until the packets are fully recovered, such as fountain codes [19], [20].

Digital fountain codes [21] are more suitable for highly dynamic UWA channels, because the number of encoding packets as redundancy can be adjusted on the fly until the full recovery is achieved, making data dissemination process to adapt to diverse error rates. Furthermore, an efficient implementation of fountain codes can be realized with available encoding and decoding algorithms [19], [20] by means of simple XOR operations [22], [23]. The Luby Transform (LT) codes [19] are the first practical fountain codes, with the following encoding steps. 1) The encoder first randomly chooses a number of input packets (which is less than the total number of input packets and called degree) for the coded packet according to a degree distribution probability. 2) The selected number of packets are independently and randomly chosen from all the input packets, and are XORed together to generate one LT coded packet. The encoding degree distribution is the key to achieve high decoding success probability.

In a dual-hop communication scenario, the decomposed LT (DLT) codes can reduce decoding computation of the destination nodes. The traditional LT uses concatenated coding to reduce computation burden of the relaying nodes, which simply perform a second layer coding of the fountain-coded packets without decoding. This arrangement doubles the computation at the destination nodes [24]. Thus, DLT consists of two layers of data encoding, which are performed collaboratively by the source and relaying nodes. It is shown analytically that the asymptotic performance of DLT with two-layer random encoding is the same as that of the corresponding non-DLT code [25].

2) ARQ: With ARQ, the sender is responsible for error correction by retransmitting unsuccessfully received packets to assure transmission reliability. To this end, a packet needs to include error control bits along with data bits as redundancy. These bits are usually arranged in the form of a cyclic redundancy check (CRC), which are used by the receiver to detect errors [2]. If a packet fails in the CRC test, it is considered erroneous. Both acknowledgment (ACK) and timing schemes are used for implementation. An ACK is a short message sent by the receiver to the corresponding sender to indicate that it has successfully received the packet transmitted by the sender. If the sender cannot receive the expected ACK on what was sent when the timeout is due, it retransmits the same packet until it receives the ACK, or the number of retrials exceeds a predefined number. A negative acknowledgement (NACK) may also be sent by the receiver to tell the sender what have not been successfully received.

ARQ schemes can be divided into link-level and path level as illustrated in Fig. 2. Link-level ARQ is used by a pair of neighboring nodes to eliminate residual bit errors and retransmit collided frames. Path-level ARQ can be performed by the

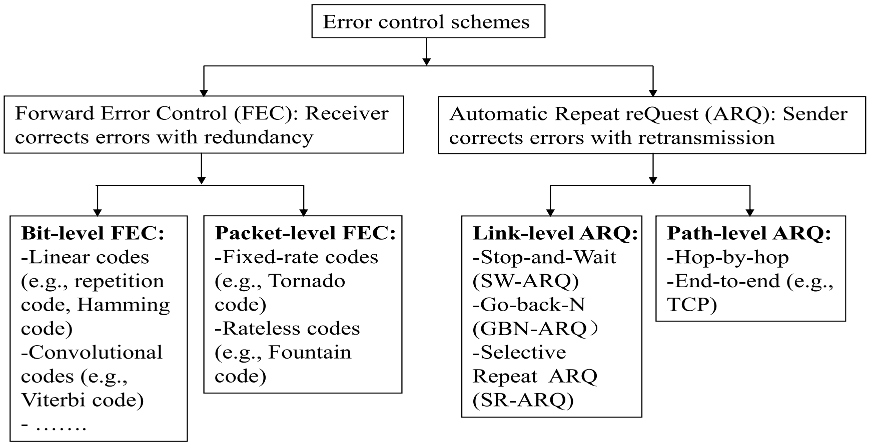

Fig. 2. Categories of typical error control schemes.

network layer to allow each link in a path to perform link-level ARQ, called hop-by-hop ARQ. It can also be carried out by the transport layer to require the source and the destination to perform an ARQ scheme such as TCP, called end-to-end ARQ, which is similar to the link-level ARQ in principle. Therefore, in the following, we introduce more the typical link-level ARQ protocols, which include Stop-and-Wait (SW-ARQ), Go-back-N (GBN-ARQ) and Selective Repeat ARQ (SR-ARQ).

a) SW-ARQ: With SW-ARQ, after transmitting a data packet, the sender cannot transmit any other data packets until it has received the ACK for the previously transmitted one. The receiver must transmit an ACK immediately to the sender after it has successfully received the packet transmitted by the sender. Once the sender receives the ACK, it continues to transmit another packet if any. If the sender has not received the expected ACK after timeout, it will retransmit the same data packet. The major weakness of SW-ARQ is the waste of channel resources caused by the blocking of transmitting other packets during waiting period for the expected ACK, especially when the propagation delay is large in UWANs.

b) GBN-ARQ: With GBN-ARQ, a sender can continue to transmit data packets even without receiving the ACKs on previously transmitted ones. The receiver keeps track of the sequence number of the next data packet that it expects to receive, and drops any others. Similar to SW-ARQ, once the receiver successfully receives the expected data packet, it acknowledges the sender of the reception. If the sender finds that a transmitted data packet has not been received successfully via either timeout or an NACK, it goes back to this failed data packet and retransmits not only this packet but all those that have been transmitted following it.

c) SR-ARQ: The main difference of SR-ARQ from GBN-ARQ is that the receiver continues to accept data packets and acknowledge each that has been received successfully even when erroneous packets are received. The sender retransmits only those packets that have not been positively acknowledged by the receiver.

C. FEC Versus ARQ

TABLE I
COMPARISON BETWEEN FEC AND ARQ

Compared items	FEC	ARQ
Errors corrected by	Receiver	Sender
Information redundancy	Larger	Smaller
Error control delay	Shorter	Longer
Necessity of feedback channel	No	Yes
Protocol complexity	Lower	Higher
Computational complexity	Higher	Lower
Bandwidth consumption	Larger	Smaller
Reliability guarantees	Hard	Easy

Table I lists the primary characteristics of FEC and ARQ. FEC can yield a short delay for error control because it does not require retransmission of erroneous packets. No feedback channel is required so that it can be used in situations where retransmission is costly or even impossible, such as massive data storage devices to protect against damage. However, the transmission of large redundancy consumes more channel resource and energy, and sophisticated coding algorithms are needed for optimal tradeoff between error control efficiency and channel utilization. ARQ does not require complex coding algorithms nor large redundancy for error control. However, a feedback-channel is required for acknowledgement, and error control delay is longer due to retransmission.

Note that FEC can optimize while ARQ can guarantee transfer reliability. They may coexist in one system because FEC can reduce the number of retransmissions and shorten error control delay, while ARQ eventually ensures transfer reliability. Particularly in layered RF wireless networks (RWNs), a bit-level FEC is usually implemented on the physical layer while ARQ on the data link layer to provide link-level reliable transfer against residual bit errors and collision. Furthermore, ARQ as well as packet-level FEC protocols are also implemented on layers above the data link layer to provide end-to-end reliable transfer against packet loss.

III. CHANNEL QUALITY CONTROL

Channel quality is the basis for reliable communication, and affected by signal reception performance that can be improved by channel modelling against noise and interference. Improved channel quality can reduce redundancy required by FEC, while increased channel capacity can allow more redundancy to be used by FEC when necessary. Several schemes have been investigated to model UWA channels and improve their quality and capacity, and some examples are introduced below to help understanding the entire reliable transfer architecture mentioned above following a brief description on UWA channels.

A. Underwater Acoustic Channels

The following features characterize UWA channels as summarized in the literature, and many examples are illustrated by measurements conducted in [4].

1) Slow & Time-Varying Propagation Speed: Acoustic wave propagation speed in seawater is approximately 1.5 km/s, and is further affected by temperature, salinity and depth [26], leading to time-varying propagation speed. Slow propagation speed causes non-negligible Doppler effect in a mobile UWAN as discussed in Section III-A4, resulting in considerable frequency shifting and motion-induced distortion [27], which may contribute to dynamics of channel quality.

2) Small & Crowded Channel: Only a limited acoustic bandwidth of maximal kHz is feasible for underwater communication, and is further shared by other underwater applications such as localization and navigation. The channel capacity is affected by frequency-dependable signal-heat conversion and spreading loss, which both increase with signal propagation distances, limiting long-range transmission rate. Achievable acoustic channel data rates versus communication distances are as follows: about 100 kbit/s for short ranges $\leq$ 1 km, 10 $\sim$ 50 kbit/s for medium ranges 1 $\sim$ 10 km, and 10 kbit/s at 20 km [28].

3) Unreliable & Time-Varying Channel: Multi-path propagation causes a signal from a source to arrive at the receiver via different paths with phase shift [29]. It is caused by acoustic signal reflected from bottoms, surfaces and floating objects etc. These out-of-phase simultaneously arriving signals may interfere with those for subsequent symbols. Another factor impacting UWA channel quality is plentiful underwater noises, which mainly includes ocean ambient noise and self-noise of vessels [30]–[33]. They typically affect acoustic communications as follows: turbulence noise for communication $\leq$ 10 Hz, shipping noise for that ranging from 10 to 100 Hz, wave and other surface motion caused by wind and rain for that 100 $Hz \sim 100\ kHz$ and thermal noise for that > 100 kHz, respectively [33], [34].

UWA channel quality may change in very short time intervals [35]. A measurement of a 3000m-long link in a 100m-deep water column shows oscillations of the average signal-to-noise ratio (SNR) of a channel equalizer about $9 \sim 5.7$ dB within about 0.5 minute, and about $9 \sim 3.5$ dB within less than 1.5 minutes [36]. It also shows large BER oscillations in short time intervals as follows: BER drops from 0.11 (with one equalizer) and 0.06 (with four equalizers) to 8.1×10^{-4} within about 2 s, both with periodic increase. As discussed in [37], channel coherence time can be in an order of 40 ms.

4) Non-Negligible Doppler Distortion: Due to the slow propagation speed, Doppler effect becomes more severe as its magnitude is proportional to ratio $\alpha \triangleq \frac{v}{V_x}$, where v is the relative speed between transmitter-receiver pair and V_x is propagation speed. This effect causes motion-induced distortion by spreading the bandwidth (B) of the received signal to $(1+\alpha)B$ (called Doppler spreading) and shifting the reception frequency (f) by an offset of αf (called frequency shifting) [27]. In UWANs, $\alpha = 2 \times 10^{-3}$ for an underwater vehicle moving at $v = 3\ m/s$, leading to a distortion contributing to dynamics of channel state, which requires frequency synchronization for efficient reception.

5) Wideband Channel: Systems whose bandwidth is smaller than 1% of the center frequency of the signals are called narrowband, and those between 1% and 20% are called wideband, while the others are called ultra-wideband (UWB) [3]. Popular frequency bands used by acoustic communication vary with communication ranges. For example, a popular frequency band is about 8 $\sim$ 14 kHz for ranges up to a few kilometers, while the upper-frequency limit is 10 $\sim$ 100 kHz [28], [29]. The bandwidth of an acoustic signal is often on the order of its center frequency, making acoustic signals quasi-UWB [27]. Therefore, UWA channels can be qualified as wideband at least [3]. This makes the popular narrowband channel model inappropriate [4]. The measurements and analysis of acoustic propagation effect conducted in [3] and [4] demonstrate the shortcomings of narrowband channel models in this case.

Wideband UWA channels are typically characterized by frequency-dependent fading statistics including the mean reception power, time-varying delays and frequency-dependent fluctuation rates. In this case, the framework of wide-sense stationary uncorrelated scattering, which is developed for narrowband systems using correlated scattering to mean correlated taps, is not applicable [4]. Frequency-dependent fading statistics includes frequency-dependent path losses (i.e., bottom loss and surface loss), absorption of seawater and scatter in the water column. Frequency-flat and frequency-selective fading may occur in multipath environments, where a channel may have paths with different Doppler shifts, leading to frequency-dependent fluctuation rates [4].

B. Proposals for UWA Channels

This section discusses UWA channel quality control from the point of view of channel modeling, modulation/demodulation and exploiting of spatial diversity as illustrated in Fig. 3. These proposals may jointly use interference alignments, and power control as well as cooperative communication as summarized in Table II.

1) Channel Modelling: As mentioned earlier, UWA channels are time-varying with frequency-dependent channel statistics, which make channel modelling difficult and complex. A statistic study demonstrates that the sound scape in warm shallow water is impulsive due to snaps created by the snapping shrimp populace inhabiting therein, and the noise realization also exhibits dependency between closely spaced samples [38]. The implicit memory of such process causes impulses to cluster together to make the process bursty. However, these features cannot be characterized by a Gaussian noise process typically used digital RF communication systems. Then a

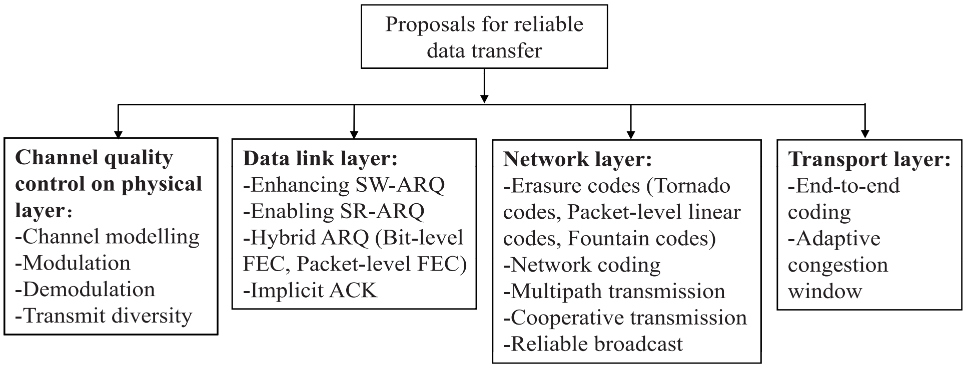

Fig. 3. Classification of proposals for reliable data transfer in UWANs.

stationary α-sub-Gaussian noise with memory order m model, αSGN(m), is discussed in [39] to make acoustic systems operating in warm shallow water to be robust against impulsive noise caused by snapping shrimp colonies [40]. This model characterizes both the impulsiveness and burstiness of a noise process, and an optimal detector is then derived based on it.

The burst error characteristics of UWA channels is also analyzed in [41], where a channel model based on a simple Fritchman model [42] is derived. The Fritchman model is a partitioned finite-state Markov chain (FSMC) [43] with one error state and $N - 1$ error-free states. It is used to model error characteristics in time-varying fading channels with the channel state being the output of a Markov chain. The parameters of the proposed model are derived from the experimental data, while the burst error distribution as well as error probabilities are calculated and compared with the experimental results. More studies are required to make the model to have realtime adaptability to time-varying UWA channels.

2) Modulation: A joint design framework of FEC and modulation is discussed in [44] and [45] to maximize the rate of successfully received bits. A modulation system can decide the best modulation scheme and its constellation to either maximize the transmission rate or minimize channel BER with high energy efficiency. The communication performance can be optimized by jointly selecting the proper code scheme for FEC (e.g., BCH) and the modulation scheme. Such kind of design tries to decide an optimal combination of the modulation scheme and its constellation as well as transmission power, FEC types and its strength to minimize both BER and packet error rate (PER). A distributed cross-layer communication solution is further studied by taking into account the primary networking functions of other layers, including medium access control (MAC) and routing, allowing efficient and fair sharing of UWA medium. Such jointly designed scheme inevitably complicates decision process, and the amount of time needed to make an optimal decision will affect its feasibility on realtime.

In shallow water, a receiver may receive multiple replicas of the same signal due to reflection off the water surface and the bottom as well as scattering from heterogeneous water. These signals superimpose on each other and deform the signal in amplitude and phase. They are also close in time with low attenuation, and their energy is comparable with that of the information signal. These effects severely limit the modulation performance [46]. Therefore, an adaptive pulse-position-modulation (PPM) acoustic detection scheme is proposed in [47] to reduce BER for very shallow water through a joint consideration of synchronization, channel knowledge and external interference. Such joint design may suffer the similar problem as mentioned above.

A Super-Nyquist (SNQ) modulation approach with SNQ signaling is investigated in [48] to provide high throughput in UWA channels. In SNQ signaling, higher rates can be achieved by increasing the signaling rate, which is decoupled from the transmission bandwidth, and can greatly exceed the transmission bandwidth [49]. However, SNQ signaling introduces severe inter-symbol interference (ISI), which limits its practical application in RF systems. Actually in UWA channels, severe ISI also exits even in the case of Nyquist signaling so that the additional ISI introduced by employing SNQ signaling is much less significant. As such, SNQ signaling is a feasible candidate for future UWA modems. When a low rate feedback channel such as one for ARQ is available for transmitters to obtain channel state information (CSI), a much higher target rate can be achieved for reliable transmission. Similarly in [50], a feedback channel is also used to allow a transmitter to obtain limit CSI (e.g., BER) in order to run a realtime algorithm for the redundancy allocation to each transmission over a link. The amount of redundancy is chosen according to an optimization framework depending on the channel BER and the number of information bits to be transmitted. However, this scheme relies on the availability of the CSI and a feedback channel.

An adaptive modulation scheme for UAW channels is analyzed in [51], by assuming that a transmitter has perfect CSI, i.e., the SNR for the current transmission. This scheme tries to tune the constellation size of the used modulation to optimize transmission rates for time-varying channel conditions according to the CSI. Both analytical results and simulations show that the scheme can satisfactorily capture the statistics of the channel if the estimation of the relevant parameters (e.g., SNR) is repeated in the case of macroscopic channel variations. The performance of a system jointly using three basic digital modulation schemes (i.e., PSK, QPSK and FSK) and several coding schemes, i.e., Trellis Coded Modulation (TCM), Viterbi coding, Turbo coding and LDPC, in UWA channels have been investigated in [52] through numerical evaluation. The most significant observation is that BER can be reduced by choosing strong signal strength, using slow and robust modulation schemes or applying channel coding schemes.

3) Demodulation: In RWNs, multichannel equalizers exploit diverse signal signatures received on spatially separated antennas to achieve further signal enhancement and better interference cancellation, so that multichannel receivers are exploited to improve acoustic communication rate in UWANs. Multichannel equalization to a single hydrophone (equivalent to antennas used in RWNs) is investigated in [53]. It equalizes jointly contiguous frequency bands carrying identical symbol streams with a process of joint equalization and despreading. For fast convergence and tracking, the multiband equalizer uses a recursive least square (RLS) update algorithm, resulting in a complexity reduced by a factor equal to the number of frequency bands through equipping all bands with separate RLS schemes and minimizing a common mean square error. These algorithms are tested on acoustic data from the Baltic Sea, showing an overall SNR improvement in three different channels.

To handle impulsive noise in warm shallow water mentioned in Section III-B1, an adaptive channel-estimate-based decision feedback equalizer (CEB-DFE) is investigated to identify and suppress noise impulse [54] following a framework able to systematically generate sparse robust adaptive algorithms proposed for RWNs in [55]. The CEB-DFE assumes that the passband noise can be modeled by a distribution defined by means of its characteristic function $\psi(\omega) = e^{-(\delta|\omega|)^{\alpha}}$, where $\alpha \in (0, 2]$ is the characteristic exponent controlling the heaviness of the probability density function (pdf) tails, while δ is the scale parameter controlling the spread of the pdf around zero. The fractile-based estimators [56] are used to estimate these parameters from the ambient noise.

4) Transmit Diversity: As widely proved in RF wireless communication systems, transmit diversity can be used to combat signal fading and minimize ISI for independently transmitted signals because the probability that all of them will fade at the same time is very small. MIMO is a widely accepted technique that can improve channel capacity and quality using transmit diversity with the following key assumptions. The channel is invariant during the transmission of a frame, and the CSI is known perfectly by the receiver [57], along with an implicit assumption that the target impulse response (TIR) energy is always concentrated in adjacent taps [58]. However, UWA channels are rapidly changing, while their impulse responses are often sparse. References [58] and [59] develop a MIMO sparse partial response equalizer (SPRE) by using the RLS algorithm for shallow-water horizontal UWA channels. It uses a sparse TIR, whose taps coincide with the multipath arrivals of the original channel, and a structure combining SPRE and a belief propagation (BP) for a coded systems can reduce the resulting error rates. BP refers to a near-optimal, graph-based and low-complexity symbol detection algorithm discussed in [60].

In many underwater systems, limited spaces make it difficult to implement line array for having necessary diversity for MIMO to achieve performance gain [5], [61]. An approach similar to virtual MIMO [62] is discussed in [61], using widely distributed nodes in UWANs to provide virtual source diversity to realize sufficient transmit diversity. It is shown with at-sea data that two sources are sufficient to minimize the BER. A similar approach is also discussed in [63], where a MIMO-based hybrid ARQ scheme (uwMIMO-HARQ) is proposed to exploit transmit diversity offered by multiple antennas. The coordination of the distributed sources is a key and difficult issue to achieve high MIMO performance because transmission synchronization from different sources is necessary.

IV. DATA LINK LAYER

Reliable transfer schemes implemented on the data link layer attempt to provide 1-hop reliable transmission between two adjacent nodes, typically including those enhancing SW-ARQ, enabling SR-ARQ and using hybrid ARQ as well as implicit ACK as listed in Fig. 3. The proposals are summarized in Table II.

For half-duplex links provided by most commercially available UWA modems, SW-ARQ can be directly applied, but its throughput is low because the channel is idle during the waiting period for ACKs as mentioned earlier. Actually, its efficiency also depends on packet sizes, link delay and link quality, and there exists an optimal packet size for the maximum efficiency [64]. Therefore, many schemes have been proposed to improve its performance in UWANs. As mentioned earlier, GBN-ARQ and SR-ARQ can outperform SW-ARQ by duplexing packet transmission and ACK reception with full-duplex links. Thus, there are several proposals aiming to create full-duplex UWA links.

To support full duplex operation, a channel can be split into two sub-channels: one for transmission and the other for reception. This can be achieved by using either frequency-division duplex (FDD) or time-division duplex (TDD). However, dividing a bandwidth-limited UWA channel with FDD will reduce data rate because a guard band is needed between two subchannels. TDD requires time synchronization, which is another difficult issue in UWANs [65], [66]. Furthermore, the time used by a node to switch between transmission and reception states affects channel utilization. For both, possible asymmetric traffic loads in two directions have to be considered further in order to maintain channel utilization.

A. Enhanced SW-ARQ

A SW-ARQ scheme is implemented in the Seaweb network [68], which adopts a MAC protocol based on a handshake protocol using two short frames: Request-To-Send (RTS) and Clear-To-Send (CTS). The transmitter first sends an RTS to the receiver, which will reply with a CTS upon receiving the RTS. Only after receiving the CTS, the transmitter sends the data frame. Upon receiving a corrupted data frame, the receiver issues an NACK frame to the transmitter to request a retransmission of the corresponding data frame. However, the overall system performance is not so satisfactory mainly due

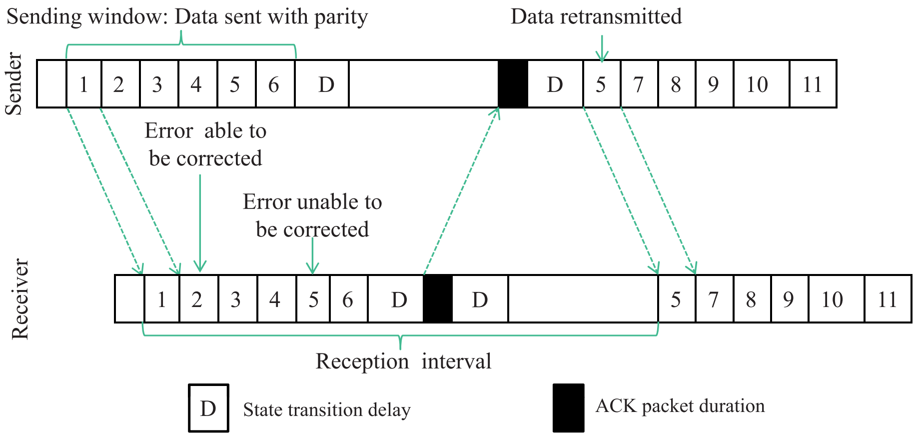

Fig. 4. Type-I HARQ for sending window $M = 6$ [67]: after 6 data packets are transmitted, the sender switches to listening to the returning ACK. For error packets 2 and 5, packet 2 can be corrected by the receiver, whereas packet 5 is retransmitted by the sender in the next sending window, along with new data packets $7 \sim 11$.

to low bandwidth utilization caused by the Frequency Division Multiple Access (FDMA) protocol.

The following mechanisms have been proposed to enhance SW-ARQ against the peculiar features of UWANs mentioned earlier. Typically, with the group transmission or packet-train approaches, a group of packets can be transmitted without waiting for the acknowledgement on each packet one-by-one. Actually, this kind of enhancement is similar to modifying SR-ARQ to run over half-duplex UWA links to be discussed in Section IV-B. Note that such kind of scheme does not eliminate the waiting time for returning ACKs but only reduces such time.

One of the earliest packet train schemes is discussed in [6], using accumulative acknowledgement. That is, a transmitter sends M packets and then stops to wait for the ACK. Accordingly, the receiver will wait for an M-packet duration and then send one ACK for all those received successfully. Once positively acknowledged, the transmitter will send another group of M packets including the unacknowledged packets and new packets. Both positive and negative acknowledgment schemes have been discussed. As analyzed in [2], the throughput efficiency of this kind of scheme can be maximized by selecting optimal packet sizes as a function of transmission range, transmission rate and error probability as well as M. Therefore, how to set optimal packet sizes on-line adaptively according to realtime situation is an important issue.

Similarly, a continuous SW-ARQ or juggling-like ARQ (J-ARQ) scheme is investigated in [69] to further leverage long propagation delay in UWANs. It also allows a transmitter to continuously transmit M data packets at the beginning without waiting for the expected ACK corresponding to an earlier transmitted data packet rather than the most recently transmitted one. The setting of M increases with the round-trip time (RTT) so that long propagation delay can be leveraged. To this end, a node should be able to finish its transmission and switch to listening by the time when the packet arrives. The accuracy of RTT measurement affects the protocol performance. Analytical and numerical studies in [70] show that J-ARQ can provide good data streaming throughput but not for small data transfer. Thus, a rateless code J-ARQ is proposed to overcome this limitation, by allowing the packets encoded for a file to be transmitted without waiting for ACKs. The transmitter is informed only when enough packets have been received to recover the file.

Similar to J-ARQ, the Stop and Wait with Exponential Retransmission (SW-MER) protocol proposed in [71] also allows M packets to be transmitted together, but they are also acknowledged together. Those having not been positively acknowledged will be retransmitted. However, the scheme uses a predefined number of packets for retransmission regardless of channel conditions, which may cause unnecessary copies of the same packet to be retransmitted. This problem is solved by an adaptive retransmission scheme proposed in [72], which changes the number of copies to be retransmitted according to the channel quality. To this end, the receiver uses ACKs returning to the transmitter to indicate which packets have been received correctly or in error.

B. Enabling of SR-ARQ

A straightforward way to enable SR-ARQ in UWANs is to create full-duplex UWA links using either FDD or TDD. FDD-based GBN-ARQ and SR-ARQ schemes are discussed in [73] for multi-hop UWANs. Each node uses three different frequency bands: one for packet transmission, another for receiving packets from its predecessor, and the last for receiving the ACKs from its successor. In this case, a node can transmit multiple unacknowledged packets without waiting for ACK. The packets correctly received can be forwarded toward the destination without effect on the reception from the predecessor. A guard band is necessary between the two subchannels, and the feedback channel will be under-utilized if there is no sufficient traffic from the receiver to the sender.

In [74] and [75], a TDD-based full-duplex channel is established for an SR-ARQ scheme, called Underwater Selective Repeat (USR), which tries to leverage long propagation delay in UWANs. USR packs several data packet transmissions within the same RTT, while keeping the receiver silent when it is expected to receive ACKs. The RTT is defined as the time interval between a data packet transmission and the reception of the corresponding ACK, and is estimated by measuring the time for exchanging a data packet and the corresponding ACK. At the beginning, a node adopts a SW-ARQ protocol to send only one data packet, and then waits for the corresponding ACK. If no ACK is received, the node will repeat the above procedure after a backoff. When the ACK is received, the node estimates the RTT, which is used by the node to estimate the maximum number of packets that can be transmitted before it enters the state waiting for ACKs. The transmission of data packets and the reception of ACKs are interlaced in time so that the same channel is used for both data communication and feedback. Actually, it seems that USR still operates in a half-duplex mode but with waiting time adaptive to RTT.

Another enhanced SR-ARQ for a full-duplex UWA link, Selective Repeat with a Second Replica ARQ, $(SR)^2$ARQ, is discussed in [76]. Different from the classic SR-ARQ, upon receiving an NACK, $(SR)^2$ARQ schedules two retransmissions: one going immediately and the duplicate being put in an additional queue and to be released after further retransmissions. The additional queue works as a fast track for packets with pending ACK, which will be injected on the channel more often than with the classic scheme. Such design aims to cater for applications requiring in-order packet delivery with complex buffer management.

C. Hybrid-ARQ (HARQ)

HARQ schemes have also attracted lots of attention to improve ARQ performance in UWANs. Such kind of scheme jointly uses the following erasure codes [77] with ARQ: bit-level FEC on the physical layer (i.e., cross-layer designed) and packet-level FEC on the data link layer (i.e., jointly designed).

1) Bit-Level FEC: An ADaptive rELIable traNsport (ADELIN) protocol is discussed in [78], and renamed as Adaptive Redundancy Transport Protocol (ARRTP) with more results present in [79]. It jointly uses bit-level FEC codes (e.g., BCH and RS codes) as redundancy schemes and a packet-level erasure code to guarantee data transfer reliability according to internode distances without using retransmission. That is, different redundancy schemes are selected for different internode distances for better performance of transfer control. It also exploits the broadcast property of UWA channels to enable cooperative communication to reduce energy consumption and improve transfer reliability. Its performance is affected by measurement accuracy of internode distances, and more overhead may occur for redundancy scheme selection in mobile UWANs.

Two types of HARQ schemes for a half-duplex UWAN are discussed in [67], jointly using random binary linear coding as bit-level FEC with ARQ. With Type-I HARQ as illustrated in Fig. 4, the sender transmits a data packet to the receiver and waits for the ACK. If the received data packet is error-free or the errors can be corrected by the receiver itself, an ACK is returned to the sender, which then can send new data packets after receiving the ACK; otherwise, retransmission will be triggered for the unsuccessful packets.

With Type-II HARQ as illustrated in Fig. 5, the sender calculates a parity packet for each transmitted packet. The packet received in error will not be dropped, and the receiver asks the sender to transmit the parity packet for error correction. The correction will be successful if the parity packet is received error-free, otherwise, error correction may fail. In the latter case, a data packet retransmission is triggered, while the previously received parity packet will be still used for packet recovery when necessary. Similarly, parity packets may also be retransmitted. These two retransmissions take place alternately until the reception is successful subject to a pre-defined maximum number of retransmissions. In [80], the above two HARQ and USR [75] (Section IV-B) schemes are investigated by simulation for a star-topology single-hop multiuser UWAN based on TDMA. The results show that HARQ performs better than USR in terms of network throughput and average packet transmission delay. An important issue is how to tradeoff adaptively between reducing redundancy transmission and minimizing error correction delay in time-varying UWA channels.

Reference [81] also suggests allowing extra parity symbols to be opportunistically included in the data packet to increase transfer reliability for a small-scale UWAN using a TDMA-based scheduling protocol. In this case, the guard time interval between time slots is usually set proportional to the maximal detection range of modems so that the actual propagation delay for a communication link in small-scale UWANs may become much shorter than the maximal expected delay, resulting in a sizeable overhead for each transmission. This scheme proposes an alternative approach to leverage long propagation delay in UWANs. Instead of transmitting more packets or ACKs during waiting time, it adaptively adjusts channel-code rate according to the CSI following the distance to nearby nodes rather than the SNR used by conventional schemes. With this CSI, which is supposed known by the transmitter, the available portion of the time slot is used to adapt its code rate when the guard time interval is longer than that required for collision-free transmission. Two possible implementations for this scheme are also discussed, one using a bank of codes and the other with rateless codes. Both simulation for typical UWA environments and experiment for a sea trial are conducted, demonstrating that, when the CSI is available, the scheme provides significant gains in terms of reliability and transmission energy consumption in comparison with the fixed coding schemes. Its performance largely depends on the availability and accuracy of CSI.

2) Packet-Level FEC: Although rateless codes are favorable for reliable point-to-point data transfer in UWANs [82], the feedback channel is either eliminated during the transmission from the sender to the receiver, or dedicated to transmit only ACKs or stop information from the receiver to the sender after a number of packet transmissions. This excludes a possibility for the receiver to send urgent data to the sender or exploiting the feedback channel to obtain timely CSI. On the other hand, packet train is inefficient for the transmission of small volume data because the optimal number of packets in a train is usually large (e.g., $M = 16$ [2]). Thus, an interwoven order scheme for ongoing packets to increase the efficiency for both rateless code schemes as well as packet train is investigated

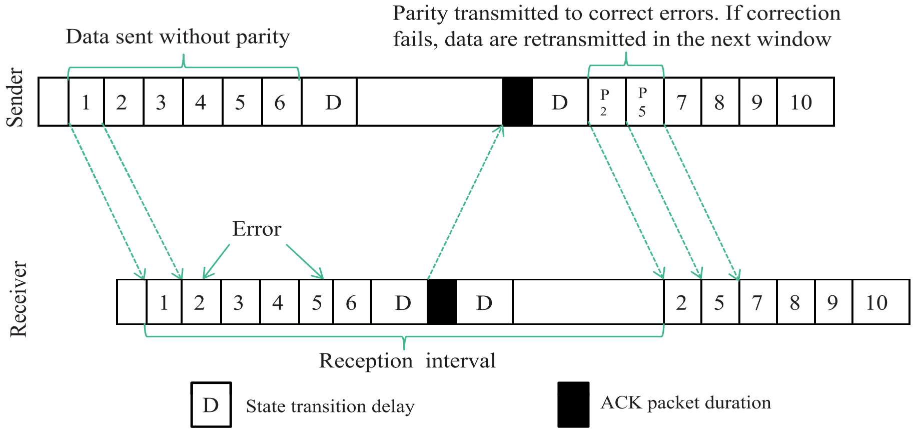

Fig. 5. Type-II HARQ for $M = 6$ [67]: for error packets 2 and 5, the receiver asks the sender to transmit their parity packets P2 and P5. Only P2 can successfully correct packet 2, and packet 5 is retransmitted.

in [83] and [84]. This scheme splits a packet train into two portions with the first portion to be sent earlier. The sender interrupts for a duration to receive the packet expected over the feedback channel, and then the second portion is sent without waiting for the feedback packet. Such arrangement aims to make the transmission to stop nearly before the arrival time of the expected packet on the feedback channel to reduce waiting time. To this end, a node needs to measure the propagation delay between communicating devices during handshaking. Tracking changes in the propagation delay during data transfer is also possible to support communication between moving stations.

The traditional LT code needs to know the whole information of the file to be encoded, which however is not available for realtime data traffic. A data-link transfer protocol using a sliding LT code (SLTC) for a tree-like UWAN is discussed in [85] to support stream realtime data transfer. It modifies the traditional LT code by using a finite length of LT codes to encode messages generated on realtime. With SLTC, all input symbols are divided into equally sized blocks. The encoding process starts from the first block to the next one, one by one. During this process, the symbols of one block are encoded according to the encoding overhead ratio and BER, which affect the adaptability of SLTC to time-varying UWA channels. Therefore, how to make them adaptive to the realtime channel condition is an important issue.

A stochastically optimized fountain code based transmission scheme is discussed in [86] to improve the goodput over time-varying UWA channels by reducing decoding overhead through controlling the parity ratio in fountain codes. It formulates the scheme as a stochastic optimization problem, which is solved using discrete stochastic approximation with each iteration adaptive to the channel state estimation.

D. Implicit Acknowledgment

To reduce ACK transmission on the data link layer, an implicit ACK scheme is investigated in [87] for a multi-hop UWAN. Due to the broadcast nature of wireless media, after a node transmits a packet, it may overhear that its next-hop neighbor is relaying the packet. This overhearing can serve as an implicit ACK for the successfully reception of the packet to avoid sending an explicit ACK [88]. A modular and lightweight implementation of this scheme in a shallow underwater environment is investigated in [89] by using inexpensive UWA modems. A similar scheme investigated in [90] attempts to control the packet size such that packet transmission time is set smaller than the propagation delay by jointly using scheduling to support concurrent bidirectional transmission in a half-duplex mode. These schemes may not work well for asymmetric links.

High BER in UWANs may cause implicit ACK to be received in error, which triggers unnecessary retransmission of successfully received packets. Therefore, an additional explicit ACK protocol is proposed to piggyback the ACK to each data packet. It also decides when to use the implicit ACK or the explicit ACK according to the per-hop BER. This scheme is improved in [91] to allow overhearing to occur in all directions and all types of data instead of the single direction and single type of data in the original scheme, i.e., overhearing is carried out in both directions, using both DATA and ACK packets.

V. NETWORK LAYER

Reliable transfer schemes on the network layer attempt to provide end-to-end reliable transmission through hop-by-hop reliability control. Many schemes jointly use various erasure codes, network coding, multiple path transmissions and cooperative transmissions as listed in Fig. 3. There are also several HARQ-based schemes proposed for reliable broadcast, which are discussed at the end of this section. The proposed schemes are summarized in Table II.

A. Erasure Codes

The typical erasure codes used by proposals schemes include Tornado codes, packet-level linear codes and fountain codes. The performance of end-to-end and hop-by-hop erasure codes for data transfer in UWANs is analytically evaluated in [92]. With a hop-by-hop scheme, each relaying node encodes packets before forwarding them to the next hop. The analytical results for RS codes show that hop-by-hop schemes outperform end-to-end ones. Based on this finding, an Erasure Code based Multi-hop Reliable Data Transfer (ECRDT) scheme is proposed to use either hop-by-hop or end-to-end erasure codes. With the hop-by-hop scheme, each relaying node computes the number of encoding packets sent to the next hop adaptively according to the perceived PER of the corresponding link [92]. The end-to-end scheme actually is performed on the transport layer, and will be discussed in Section VI.

1) Tornado Codes: A HARQ scheme, called Segmented Data Reliable Transport (SDRT), is investigated in [93]–[95] to provide reliable transfer across the network. The source node first groups packets into blocks of size m, and then encodes each block using a simple variant of Tornado codes - a two-layer Tornado code. The data packets are forwarded from the source to the destination block by block. During each hop-by-hop relaying, the sender first transmits a pre-estimated number of encoded packets (called sending window size) so that the receiver can recover the original packets. Then, the sender slows down the transmission to wait for ACKs. If no positive ACK is received after the times-out, one encoded packet is sent to the receiver and so on until the expected ACK is received. However, this ACK does not inform the sender of which packets are missing and necessarily retransmitted. Thus, a Underwater Hybrid ARQ (UW-HARQ) is proposed in [96], additionally adopting an NACK to inform the sender of the number of encoded packets to be sent for decoding. Furthermore, a random binary linear coding scheme is adopted to minimize coding and decoding complexity. However, its fixed code rates cannot adapt to time-varying UWA channels.

2) Packet-Level Linear Codes: Several enhancements to SDRT have been reported in the literature. A Practical Coding based Multi-hop Reliable Data Transfer (PCMRDT) protocol is proposed in [97] to handle the problem caused by practical difficulties in deciding the optimal size of the sending window of SDRT due to the computation complexity. It adopts a packet-level Random Linear Coding (RLC) due to its low coding and decoding complexity, and jointly uses a SR-ARQ for per-hop reliable transfer control. In the case of decoding failure at the receiver, SR-ARQ is triggered for retransmission until packets are successfully received. A multi-hop coordination mechanism utilizing pipelining scheme is also adopted to eliminate some collisions imposed by half-duplex UWA modems and reduce end-to-end delay. A particular RLC scheme, GF(256), is further adopted in a similar protocol, called Coding based multi-hop Coordinated Reliable Data Transfer (CCRDT) [98]. CCRDT attempts to almost 100% guarantee that K encoded packets are able to recover K data packets [88]. In this case, the code ratio estimation only depends on the PER, which can be estimated according to the information carried by ACK/NACK packets that indicate the number of packets received for the last transmission. Therefore, a feedback channel is required for the PER estimation.

Another packet-level RLC without using a feedback channel is investigated in [99] for a time-invariant UWA channel. A fixed number of coded packets are determined so that the receiver can decode the original packets with a pre-specified reliability. This scheme is extended to a fading channel for time-varying link conditions in [100], by using a framework combining adaptive power control with RLC to overcome the effect of channel fading. In [101], a feedback channel is used to allow the receiver to update the CSI to the sender so that the transmit power and code rates can be adjusted according to the channel state to minimize energy consumed per successful transmitted bit. Furthermore, the constrained resource is further taken into account. This is due to that for the minimal average energy per bit, there exists an optimal number of coded packets with adaptive power control as well as an optimal transmit power with adaptive rate, too.

3) Fountain Codes: A FOuntain Code based Adaptive multi-hop Reliable data transfer (FOCAR) protocol for multi-hop reliable data transfer is investigated in [23]. FOCAR integrates fountain codes with a hop-by-hop retransmission-upon-failure scheme, by considering the impact of the large state transition delay of currently available half-duplex acoustic modems. With the proposed per-hop reliable data transfer scheme, after a relaying node receives packets from its upstream node, it first groups m packets into one block, and encodes the packets in each block into M packets with fountain codes. Then, the relaying node sends the M coded packets to its downstream node and switches to the receiving mode. If the downstream node can correctly decode the original m data packets, it sends a positive ACK to the relaying node; otherwise, a negative ACK indicating the number of unrecovered packets is sent. In the latter case, the relaying node will transmit more encoded packets to its downstream node for recovery. Its computation loads in relaying nodes consume lots of energy.

Another fountain-code based reliable transport and storage protocol for data-centric storage in UWANs is investigated in [102] for communication between querists and the data center. It designs a distributed fountain coding scheme for reliable data delivery, and a concatenated one for data storage reliability control. The same authors investigate a hybrid DLT (h-DLT) to ensure small end-to-end communication latency and flexible computation cost balance between the source and the relaying nodes for a relay-aided UWA communications in [103]. h-DLT encodes data in a hybrid mode: cooperative DLT mode and direct LT mode. The output packet is cooperatively encoded by both encoders in the former mode, while the packet is generated only by the first encoder in the latter mode. By choosing different combination ratios, the coding system can flexibly assign different computation loads to the two DLT encoders.

B. Network Coding

The basic ideal of network coding [8] is to allow networking units (e.g., routers) to perform packet-level coding by combining several packets together in transmission (e.g., with XOR) to increase the network transmission throughput. As illustrated in Fig. 6, packets A and B are transmitted along two disjoint side paths, respectively, and their XORed combination is transmitted once along the middle path. In this case, nodes along the two side paths can have both packets A and B with

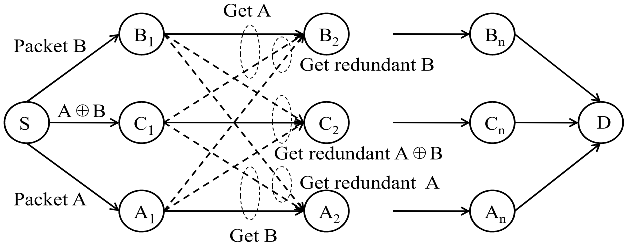

Fig. 6. Network coding and MPNC work flows (⊕: XOR operator) [104].

a simple decoding. However without such coding, each of packets A and B needs to be transmitted along the middle path for the same reception result. Note that network coding itself does not have capability for transfer reliability control. It can allow more redundancy transmission due to its higher transfer efficiency than that without network coding, and its multipath transmission property can also be used to provide transmission redundancy as well as diversity, hence improving reliability control performance. However, network coding operation should be performed hop-by-hop, and its efficiency depends on network topologies as discussed below.

Reference [105] demonstrates an improved efficiency of error control by jointly applying network coding in UWANs through simulating the following two scenarios. i) Network coding is performed only by the relaying nodes; and ii) the coding is also performed by the source nodes. The following forwarding schemes are compared: i) single-path forwarding, ii) multipath forwarding, and iii) multipath coded forwarding. The path is determined by the vector-based forwarding routing protocol in [106]. The simulation results show that network coding with source coding performs best. This work is further deepened in [107] and [108] through theoretical study, which can guide the setting of configurations for both efficient error recovery and energy consumption. The proposed scheme works as follows. The original packets from the source are divided into generations, each of which contains K packets. These packets are linearly combined into a generation using randomly generated coefficients. A relaying node in the forwarding path first linearly combines packets from different paths belonging to the same generation, and then relays them. After the destination node receives K packets, it can recover the original packets through matrix inversion [109].

A Multiple Paths and Network Coding (MPNC) scheme for a specific network structure favorable to network coding is investigated in [104] and [110]. As illustrated in Fig. 6, three disjoint paths are established between a source-destination pair. Packet groups A and B are transmitted along the two side paths, while packet group A⊕B is transmitted along the middle path. In this case, any two paths can work together to provide a redundant for another path so that any two nodes on the same level are expected to correct errors of the third node. A similar approach is also investigated for a braided multipath network model in [111], where acknowledgment nodes and feedback retransmission mechanisms are jointly used.

Particularly for a 1-hop UWAN, where all nodes in the network can hear each other, a random network-coding scheme without retransmitting the original information is investigated in [112]. It allows nodes to transmit packets that are composed of data partially originating at that node and partially received by that node from other nodes, through a random linear combination of them. All nodes receive the source messages from all other nodes, and try to decode each message. If successful, the data transfer is considered being completed. The suitability of network coding for error recovery in high BER UWA channels and the parameter settings to achieve the desired performance are also studied in [113], without assuming specific MAC and routing protocols. These assumptions are different from those adopted by the research conducted in [105], [107], and [108].

C. Multipath Transmission

Multi-path transmission can also be used to provide packet-level redundancy by making use of available bandwidth in the network to send more copies of the same packet simultaneously. Several such schemes jointly using power control and FEC have been reported in the literature. The performance of such kind of schemes depends on the availability and the number of multipaths in the network.

Large propagation delay in UWANs causes that the RTT is significantly larger than that in RWNs. For example, RTTs in UWANs are often in the order of tens of seconds, while few milliseconds in RWNs [114]. Long RTT severely degrades TCP performance when a congestion is inferred because it takes much time for the source node to restore its TCP congestion window to the normal level. In [114], a routing protocol called Linear Coded Digraph Routing (LCDR) is proposed to maximize TCP throughput in UWA mesh networks. The basic idea of LCDR is to maximize packet redundancy for lost packet recovery through making use of available bandwidth with multi-path transmissions from both the source node and relaying nodes to the destination node with network coding of TCP segments.

A Multipath Power-control Transmission (MPT) scheme is discussed in [115] to provide reliable data transfer for time-critical applications. It combines power control with multipath routing without using hop-by-hop retransmissions, working as follows. The source node first initiates a multipath routing process, through which, the source node will obtain some network parameters such as path length and the number of available paths. Then, it selects paths and calculates the optimal transmit power for each node along the selected paths, and sends the same packet along the selected paths. Each relaying node on the selected paths relays the packet with the transmit power parameters carried in the packet header. When the destination node receives all copies of the packets, it combines them to recover the original packet. It is shown that MPT can save significantly energy with low end-to-end delay.

Another multi-path transmission scheme incorporating a Hamming code-based FEC (MHC-FEC) is investigated in [116] to improve the overall redundancy for highly decoding-efficient transfer reliability. The Multicast Ad hoc On-Demand Distance Vector (MAODV) routing protocol [117] is used to establish multiple paths between the source and the destination node, while the broadcast nature of the wireless medium is used to enable a packet to be delivered in multiple paths. Each segment in the received packet is regarded as a unit to vote for packet reconstruction. A relaying node attempts to recover the corrupted segments with a Hamming decoder, and then forwards them to the next intermediate node toward the destination node, which decodes the packets with correction using multiple copies received from multiple paths.

D. Cooperative Transmissions

A cooperative transmission based reliable transfer scheme for 1-hop UWANs is investigated in [118], aiming to reduce inefficiency of error control caused by long RTTs. A node is allowed to participate in transmission to other nodes by providing another copy of the same packet to the destination node. This scheme is extended to a multi-hop UWAN in [119], allowing relaying nodes along a specific source-to-destination route to provide alternative paths. Thus, neighbors or other relaying nodes closer to the destination node may opportunistically take part in the retransmission, and these nodes are called cooperators. Whenever a retransmission is required, the destination node requests it from the cooperators first by sending a NACK, and waits for the data. After the destination node successfully receives the data, it sends an ACK to the source node, which also indicates the cooperators that the cooperative mission is completed. Furthermore, it also adopts an implicit acknowledgement using a backward overheard packet as an ACK [90].

A Cooperative Hybrid ARQ (C-HARQ) protocol is investigated in [120], using an FEC scheme based on rate-compatible punctured code [121]. A cooperation information sharing protocol using a handshake scheme is further discussed in [122]. It allows a source node to identify a list of cooperators, which is sent to the destination node. A similar approach called 2H-ACK is also reported in [123] for hop-by-hop reliability control, where every single packet will be maintained by two nodes in the network. This scheme is enhanced with a 3 Hop-Reliability Model (3H-RM) in [124], where three nodes are responsible for keeping the copy of the same successfully transferred data packet.

E. Reliable Broadcast

A reliable broadcast protocol has to control efficiently errors of the messages received by different nodes without causing retransmission storms. To this end, two hybrid FEC/ARQ reliable broadcast protocols are investigated in [125]. They leverage the relationship between communication distance and the bandwidth available for UWA links. This is due to the fact that the frequency band available for communication is reduced and shifted toward lower frequencies as distances increase [34]. Furthermore, the power control of typical underwater devices allows communication range to vary on an order of tens of kilometers [125].

With the Simple Reliable Broadcast (SRB) protocol, every node rebroadcasts a received broadcast message to its neighbors. If a node has not received all the packets of a message, it then waits a pre-defined time interval and broadcasts a retransmission request to its neighbors. The neighbors will broadcast the requested packets when necessarily. The proposed Single-Band Reliable Broadcast (SBRB) protocol expands SRB by employing long-range communication in a lower frequency but at a high-power level to notify all neighbors of the broadcast initiation. Then the node uses shorter-range transmission in a high frequency band but at a low power level to send the broadcast messages to neighbors. With the Dual-Band Reliable Broadcast (DBRB) protocol, the low-frequency band for long distances at the high power level is used to send some FEC data for error correction, which is the only difference from SBRB. The simulation study shows that both SBRB and DBRB much outperform other protocols in terms of energy consumption and completion time, while DBRB performs the best in the case of high BER.

Another HARQ reliable broadcast scheme is investigated in [22] for a UWAN, in which a source and a number of nodes are randomly placed within a given geographical area. It incorporates fountain codes into SW-ARQ to reduce the number of transmissions for reliable message dissemination to a number of nodes as much as possible. A broadcast message is divided into K original packets of fixed length, which are delivered to a number of receivers. Error recovery is carried out through a number of transmission rounds. The authors formulate the transmission process by using dynamic programming and obtaining optimal policies for minimizing the number of transmissions needed for a full recovery at all receivers. It shows that fountain codes have a number of advantages for UWA communications. A mathematical model is further studied in [126] for the above scheme, considering the specific features of the UWA channel, e.g., variation of the available bandwidth against distances. This model can also be used to understand the insight of network coding against network parameters and their effect on broadcast performance.

Three reliable broadcast protocols are discussed in [127] for a 3D UWA sensor network with different degrees of neighbor information, namely, no neighbor knowledge, 1-hop neighbor knowledge and 2-hop neighbor knowledge, using a NOTICE/QUERY/NACK process. That is, immediately before broadcasting a QUERY packet, the sender first transmits a short NOTICE. If a node has received the NOTICE but not the QUERY, it sends a NACK to inform other nodes.

VI. TRANSPORT LAYER

The large propagation delay in UWANs significantly influences the performance of end-to-end reliability control schemes such as TCP. Thus, no many TCP-like schemes have been proposed for UWANs as listed in Fig. 3. Two proposals are summarized in Table II.

As mentioned in Section V-A, ECRDT [92] also provides an end-to-end reliability control to reduce end-to-end delay to recover lost packets using redundancy. The coding operation is performed only by the source and destination nodes, and the number of encoding packets is determined according to the path-level PER, which may be out of date due to long propagation delay.

To handle time-varying characteristics of UWA channels, an Adaptive RTT-driven flow and error control scheme

(ARTFEC) is investigated for a multi-hop UWAN in [128]. It combines an adaptive congestion window (ACWND) control and a Q-learning timeout selection. ACWND uses an RTT-based data flow control to adapt to varying UWA channel environments by estimating the network status through the RTT measured according to the feedback from data and ACK packets. Q-learning is a model-free reinforcement learning technique, which can be used for estimation that can yield near-optimal policies without much computations. It uses an off-policy temporal difference approach [129], [130], in which the agent approximates Q-values iteratively. It is important to investigate learning efficiency for dynamic UWANs.

VII. DISCUSSION

This section first summarizes the primary characteristics of the reviewed reliable transfer schemes proposed for UWANs, and then discusses the different design strategies adopted by them as well as the main remaining challenging issues.

A. Remarks

Table II summarizes the reliable transfer schemes reviewed in this paper, highlighting their design points and the duplex mode of UWA links as well as coding schemes assumed or adopted by each scheme, particularly for the link-level and path-level schemes.

From the above discussion, we can find that the basic mechanisms adopted by the reviewed schemes for transfer reliability control in UWANs are still the same as those adopted by RWNs, i.e., redundancy and retransmission. The main difference is that more methods are adopted to generate redundancy rather than only using the bit-level FEC. These methods include packet-level erasure codes (Section V-A), network coding (Section V-B) and multi-path transmissions (Section V-C) as well as cooperative transmissions (Section V-D). For signal transmission and reception on the physical layer briefly reviewed in Section III-B, channel estimation based on fading and noise modelling as well as CSI capture is used in modulation and demodulation design to improve the performance. However, several schemes assume the availability of a feedback channel for CSI collection and parameter measurement such as SNQ [48].

Among the erasure code based schemes, ratelless code schemes such as fountain codes (Section V-A3) are more suitable for time-varying UWA channels. However, these schemes need a feedback channel for the sender to know whether the number of sent packets is enough for the receiver to recover the original packets, while the feedback channel can be used to guarantee transfer reliability if necessary. With the other erasure codes such as Tornado codes (Section V-A1) and packet-level linear codes (Section V-A2), it is difficult for the sender to decide an optimal code rate adaptive to time-varying UWA channels on realtime in order to guarantee reliability without retransmission. Thus, several such kind of schemes also adopt feedback channels to obtain the information necessary for setting optimal code rates or making retransmission decisions, such as SDRT [93]–[95], PCMRDT) [97], CCRDT [81], [98], and [101].

For retransmission using ARQ over half-duplex UWA links, enhanced SW-ARQ or modified SR-ARQ, such as those using packet train [2], [6], J-ARQ [69] and SW-MER [71], are relatively straightforward to enhance the original ARQ schemes to improve their performance in UWANs. However, it is difficult to allow a sender to know the best time for it to switch from the transmission mode to the reception mode so that it can receive the ACK or NACK returned by the receiver without waiting for long time, especially if the channel quality changes rapidly while mode transition time is large.

Some schemes assume the availability (e.g., [76]) of full-duplex UWA links or create such a link using either FDD (e.g., [73]) or TDD (e.g., USR [74], [75]) in order to run the original SR-ARQ or GBN-ARQ. They need to further take into account some technique limitations in the practical implementation, such as the limit bandwidth with FDD and possible large transition time between transmission and reception modes [23] with TDD. Actually, the first generation of Seaweb [131] is based on FDMA, which however results in inefficient bandwidth utilization, and was abandoned in subsequent implementations [132]. Note that, many reviewed schemes do not specify a duplex mode of UWA links, nor take into account the limitation on protocol design imposed by half-duplex UWA links as well as their effect on the protocol performance.

In comparison with RWNs, the design strategies adopted for end-to-end transfer reliability control in UWANs have the following characteristics: joint design and network-layer dominant design. Joint design can be further divided into vertically joint design that jointly uses functions or information available on different layers (i.e., cross-layer design), and horizontally joint design that combines various schemes at the same layer (e.g., hybrid design), each of which is discussed below.

B. Vertically Joint Design (Cross-Layer Design)

As mentioned above, in RWNs, FEC and ARQ usually coexist in the same system but often operate independently without interaction to each other. Such kind of implementation is suitable for channels with stable or slowly changing quality. To handle highly dynamic UWA channels, FEC and ARQ are often cross-layer designed such that ARQ can also be used to update CSI (e.g., BER). This information can be used to determine optimal parameter settings such as code rates and block lengths for FEC. The examples include SBRB and DBRB [125], Type-I and Type-II HARQ schemes [67], as well as SNQ [48] for higher channel rates based on CSI and [50].

Such cross-layer designed schemes do make sense to enable reliable transfer schemes to be adaptive to time-varying UWA channels with less redundancy while satisfying a predefined reliability requirement as much as possible. Furthermore, transfer reliability can be guaranteed with ARQ if necessary. Such schemes can be more cost-effective to ensure one-hop transmission reliability than an FEC/ARQ co-existing structure without cooperation in UWANs. However, there is still a tradeoff between the redundancy cost and the delay used to eliminate errors for successful reception, and optimization is

TABLE II

SUMMARY OF THE SURVEYED SCHEMES FOR TRANSFER RELIABILITY CONTROL (IN THE ORDER OF REVIEWING)

Schemes / Ref	D/C	Key design points	Remarks
Channel quality control on physical layer			
[38]		Model for impulsive & bursty noise	Deriving an optimal detector based on such noise model
[41]		Modelling with the Fritchman model	Model for burst errors
[44]		Joint design of FEC & modulation	Optimizing FEC and modulation selection
PPM[47]		Jointly considering SYN & interference	Adaptive modulation to reduce BER
SNQ[48]		Going beyond Nyquist rate	Leveraging UWAN features to improve channel capacity
[51]		Adaptively tuning constellation sizes	Adaptive to time-varying channels according to CSI
[53]		Multichannel equalization with RLS	SNR improvement with low complexity
CEB-DFE[54]		Adaptive channel estimate using noise model	Improved equalization against impulsive noise
SPRE[58]		Combing RLS and belief propagation	Enabling MIMO in shadow water to reduce BER
[61]		Virtual MIMO	Distributed implementation of MIMO to reduce BER
Data link layer			
[6]	HD	Packet train	Improving throughput using a reserved feedback channel
J-ARQ[69]	HD	Packet train	Transmission adaptive to RTT, affected by RTT's accuracy
SW-MER[71]	HD	Packet train with accumulative ACK	Less ACK overhead, adaptive redundancy transmission
[73]	FD	Frequency division duplexing	Guard band and feedback channel waste channel resource
USR[74]	FD	Time division duplexing	Half-duplex protocol with waiting time adaptive to RTT
$(SR)^2$ARQ [76]	FD	Double retransmissions	In-order packet delivery with complex buffer management
ADELIN [78]		Cross-layer with cooperative communication	Distance-adaptive redundancy transmission
HARQ[67]	HD	Cross-layer with separate parity transmission	Improving throughput with less delay
[81]	TDMA	CSI-adaptive coding	Adaptive to time-varying channel following CSI at senders
[83]		Splitting of packet train	Reducing waiting time, affected by propagation delay estimation
[85]		Sliding LT codes	Enabling LT codes for realtime traffic with finite code lengths
[87]	HD	Implicit ACK (IACK)	Reducing ACK overhead for symmetric links
[90]	HD	IACK with scheduling	Supporting concurrent bidirectional transmissions
[91]		IACK and ACK	Jointly using ACK & IACK for more reliable acknowledgement
[86]		Formulating of adaptive coding problem	Adaptive to time-varying channels following CSI at senders
Network layer			
ECRDT[92]	EC	Hop-by-hop encoding	Adaptive code rate following link-level packet error rate (PER)
SDRT[93]	TC	Jointly using hop-by-hop control and ARQ	Providing path-level reliability with fixed code rates, and further reducing retransmission with UW-HARQ
UW-HARQ[96]	TC	ARQ with NACK	
PCMRDT[97]	RLC	Jointly using SR-ARQ, and additionally PER estimation for CCRDT	Enhancing SDRT for less coding complexity & retransmission
CCRDT[98]	RLC		Enhancing SDRT to guarantee almost 100% packet recovery
[100]	RLC	Power control	Reducing the effect of channel fading on reliable transfer
[101]	RLC	Power control with adaptability to CSI	Minimizing energy consumption per successful transmitted bit
FOCAR[23]	HD, FC	Jointly using hop-by-hop control & ARQ	Considering impact of state transition delay of acoustic modems
[102]	FC	Jointly using distributed & concatenated coding	Tradeoff between small end-to-end latency and computation cost
h-DLT[103]	LT	Combining decomposed & direct LT codes	Flexibly assigning computation loads to encoders
[105]	NC	Designing network structures favourable for network coding	Demonstrating benefits of using network coding for reliable transfer with specific network structure
MPNC[104]	NC		
[112]	RNC	Mixing source & transient data in transmission	Increasing redundancy with more cooperative transmissions
LCDR[114]	LC	Multipath transmission	Maximizing redundancy with available bandwidth
MPT[115]		Multipath routing with power control	Supporting time-critical applications
MHC-FEC[116]	HC	Multipath with hop-by-hop control	Improving redundancy for high decoding efficiency
[118]		Cooperative transmission	Reducing error control inefficiency with long RTT
C-HARQ[120]	CC	Combining cooperative and hybrid ARQ	Improving throughput and energy efficiency
SBRB[125]		Adaptive power control	Leveraging bandwidth-distance relationship for effective broadcast, more reliable with more retransmissions for DBRB
DBRB[125]	DB	Adaptive power control, FEC	
[22]	HD	FEC and SW-ARQ	Reducing transmissions for reliable broadcast
Transport layer			
ECRDT[92]	EC	End-to-end encoding	Adaptive code rates according to path-level PER
ARTFEC[128]		Combining adaptive cwnd and Q-learning	Adaptive to time-varying network topology and channels

D/C=Duplex mode/Coding schemes: {FD/HD=Full/Half duplex, DB=Dual bands, CC=Convolution code, EC=Eraser code, HC=Hamming code, FC=Fountain code, LC=Linear code, RLC=Random LC, NC=Network coding, RNC=Random NC, TC=Tornado code}, CSI=Channel state information, cwnd=congestion window, RLS=Recursive least square, RTT=Round-trip time

still an issue for highly dynamic UWA channels. On the other hand, the feasibility of these schemes depends on the availability of feedback channels, which however cannot be always guaranteed in UWANs. Theoretical study is still necessary for further optimization, while how to achieve the optimization gain in practice is important for time-varying UWA channels.

C. Horizontally Joint Design

In many RWNs, one ARQ scheme on the data link layer is usually sufficient to provide error-free reliable data transmissions with satisfactory performance in cooperation with FEC on the physical layer. However, due to much larger propagation delay in UWANs, the performance of ARQ may become unacceptable with too many retransmissions. Therefore, various packet-level FEC schemes have been jointly used with ARQ in order to reduce the number of retransmissions and shorten delay as much as possible for successful reception. Such schemes include those investigated in [18], [83], and [84] for link-level reliability control with rateless codes on the data link layer. In comparison with the schemes cross-layered with bit-level FEC mentioned in Section VII-B, whether such hybrid design can yield better performance cost-effectively needs a further investigation, especially if a bit-level FEC scheme is already implemented on the physical layer, which is often the case with commercially available modems.

More hybrid schemes have been proposed for the network layer using either erasure codes or network coding as discussed in Sections V-A and V-B, respectively. Erasure code schemes are mainly used as packet-level FEC to combat not only transmission errors but also packet losses that might not be handled by the link-level schemes mentioned above. The design concern here is the adaptability to time-varying UWA channels. In this sense, rateless code schemes are better than those with fixed code rates such as SDRT [93] and UW-HARQ [96]. Therefore, many rateless code schemes have been investigated, typically including PCMRDT [97], CCRDT [98], [99], [101], FOCAR [23], [102] and h-DLT [103].

Another concern for coding-based schemes is computation loads of each involved node, which includes the source node, relaying nodes and the destination node. This issue mainly depends on the complexity of encoding and decoding algorithms, and affects energy consumption of each involved node. Several schemes adopt random linear codes due to its simplicity, such as PCMRDT [97], CCRDT [98] and [99], [101], while h-DLT considers the balance of computation loads between the relaying nodes and the destination nodes. However, a comprehensive investigation on the performance gain that can be achieved by such kind of reliable transfer protocols against the energy consumption of the adopted coding algorithm is still needed in order to maximize reliable transfer performance at the lowest cost in UWANs.

Error control efficiency of using network coding and its suitability in high BER UWA channels are investigated respectively in [105], [107]–[109], and [113]. Several reliable transfer schemes using network coding are also discussed, such as a random network-coding [112] and a network structure favorable for network coding operation [104], [110], [111]. To achieve network coding gain, a proper transmission path plan is useful to combine properly data from different upstream nodes as illustrated in Fig. 6 [110]. Thus, a practically feasible reliable transfer scheme jointly using network coding still require more investigation, which can jointly consider multipath and cooperative transmission to enable controllable multi-cast for network coding.

D. Network-Layer Dominant Design

In the Internet, end-to-end transfer reliability control is conducted by an ARQ-like protocol on the transport layer, i.e., TCP. This protocol simply requires the source node to retransmit the original packets until it has been positively acknowledged of the successful reception of what were sent, subject to a maximum number of retransmissions. However, in UWANs, due to much larger propagation delay, the RTT may become too long to yield acceptable ARQ performance. Thus, hop-by-hop reliability control performed by relaying nodes on the network layer become more abstractive to provide end-to-end transfer reliability. Therefore, more reliable transfer schemes on the network layer than on the transport layer have been investigated in the literature as listed in Table II, and many of them are jointly designed.

In terms of the complexity and operation load of relaying nodes, new challenging issues may be raised by the hop-by-hop reliable transfer schemes on the network layer, especially when the end-to-end transfer reliability has to be guaranteed. This is one remaining challenging issue, and is discussed in detail in Section VII-E.

E. Challenges Remaining

The above discussion demonstrates that end-to-end transfer reliability control involves the physical layer, the data link layer and the network layer as well as the transport layer. This feature is different from other networking technologies such as medium access control (MAC) protocols and routing protocols. To achieve optimal reliable transfer performance in harsh UWAN environments with less consumption of channel resource and energy, most of the above-mentioned schemes are jointly designed either vertically or horizontally. However, they lack of a systematical plan, which causes some important issues have not been well addressed, such as the overall complexity and functional distributions as well as systematical cooperation as discussed below.

As mentioned in the literature, there are no typical UWA channels suitable for different environments [4], [133]. Channel models based on long-term statistics cannot effectively adapt to time-varying channels, while those for particular underwater environments (e.g., shallow or deep waters, horizontal or vertical channels) are not suitable for mobile UWANs. On the other hand, channel model is very important to improve channel estimation accuracy for better reception performance, so it is necessary to study channel models with realtime adaptability to different underwater environments.

Although hybrid schemes using packet-level FEC can combat packet loss for end-to-end reliability control, the effect of these schemes on congestion in the network as well as congestion control itself has not been taken into account. Actually, all these schemes adopt redundancy using different coding algorithms, while redundancy will lead to more traffic loads, which may lead to more congestion as well as more losses if no proper congestion control is in place. On the other hand, as discussed for Semi-TCP [134]–[136], congestion control functions can be piggy-backed with link level functions such as MAC or logical link control for hop-by-hop control, while many reviewed schemes also adopt hop-by-hop reliable transfer schemes for end-to-end transfer reliability control. Therefore, it is necessary to consider jointly them to further improve reliability control performance with less consumption of channel resource and energy.

For horizontally joint schemes using packet-level FEC, they do not specify that no bit-level FEC schemes are implemented on the physical layer. However in practice, bit-level FEC schemes might be embedded on the physical layer (e.g., [137]). In this case, if a packet-level FEC design does not consider the bit-level FEC scheme, more redundancy and more computation for encoding and decoding operations are inevitable, and both cause more consumption in channel resource and

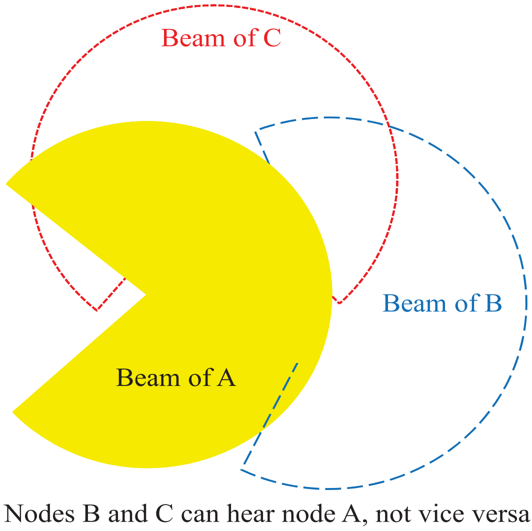

Fig. 7. Scenarios for asymmetric link connectivity [139], [140].

energy. These features are undesirable in UWANs so that a joint consideration of these coding schemes is necessary.

As discussed above, many hop-by-hop reliable transfer schemes on the network layer have been proposed, while the transport layer function is almost ignored. Such design imposes a challenge to relaying nodes when end-to-end transfer reliability guarantee is necessary. Although redundancy can allow a certain number of packet droppings, it is very difficult to decide such an optimal number so that end-to-end successful reception can be guaranteed, especially for time-varying UWA channels. In this case, each relaying node should store the packets that are relayed by itself until they have been successfully received by its downstream nodes or their lifetimes are due. This means that the relaying node should have a large buffer and buffer management becomes an issue, especially if the node has many packets to be forwarded to different neighbors. This requirement can be relaxed to certain degree by the transport layer function, such as TCP in the Internet. However, such kind of systematical cooperation has not been addressed so far.

In a word, an optimal design for end-to-end transfer reliability control in UWANs requires a systematical plan for function distribution and cooperation from the physical layer up to the transport layer, in order to minimize transmission redundancy, computation load, buffering operation as well as the consumption of channel resource and energy. Such plan needs a throughout investigation by further considering asymmetric features in UWANs that somewhat have been ignored by most reviewed schemes. Typically, these features include asymmetric UWA links, asymmetric capacity and capability as well as functions of nodes in UWANs. For example, an asymmetric link scenario may be caused by a directional beam with less than 360°-width rather than an omin-directional coverage as illustrated in Fig. 7, or by an upslope bathymetric profile, in which, the channel may experience much higher BERs in the direction toward the upslope than in the opposite direction [138]. Regarding asymmetric capacity and capability, a sink node on the water surface is usually much powerful than an underwater node in terms of communication capacity, energy supply and buffer capacity etc.

VIII. CONCLUSION

This survey, to the best knowledge of the author, is the first one that systematically reviews the typical schemes used for transfer reliability control in UWANs, mainly focusing the schemes on the data link layer, the network layer and the transport layer. Different from other networking technologies such as medium access control (MAC) and routing protocols, the performance of end-to-end reliable transfer depend on the performance of each layer mentioned above. Thus, an optimal design needs a systematical plan for distribution and cooperation of the relevant functions on these layers. This issue needs a throughout investigation with further taking into account asymmetric features in UWANs that have been ignored by most reviewed schemes here. This paper aims to provide a more complete picture of the end-to-end reliable transfer architecture in UWANs, which is useful to study optimal design of reliable transfer schemes proposed for different layers.

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