A Joint Linear-Analog Network Coding Based Protocol for Data Transfer in Underwater Acoustic Networks

Xiaobo Zhao, Xiaohong Shen, Haiyan Wang, Weigang Bai ,Ruiqin Zhao
School of Marine Science and Technology
Northwest Polytechnical University
Xi'an, China 710072
Email: xbzhao@mail.nwpu.edu.cn,{xhshen,hywang}@nwpu.edu.cn,wgbai@mail.nwpu.edu.cn,rqzhao@nwpu.edu.cn

***Abstract*—In underwater acoustic networks, the objective that researchers are pursuing is establishing a network with high reliability, high throughput and low energy consumption. Network coding can enhance reliability and throughput of network. Moreover, the throughput of network will be significantly improved by analog network coding. Accordingly, with higher reliability and higher throughput, the energy consumption will be lower. In this paper, the linear network coding and analog network coding are combined creatively. Besides, a SNR estimation algorithm is used to choose packets instead of choosing packets randomly for decoding. Afterwards, for taking advantage of the redundant packets better, packets are refreshed via bit-by-bit comparison. At last, we present numerical experiments to evaluate the performance of this scheme.**

***Index Terms*—underwater acoustic networks, linear network coding, analog network coding, transport protocol.**

I. Introduction

The research of Underwater Acoustic Networks (UANs) has received much attention recently, especially for some practical applications of UANs, such as oceanographic data collection, offshore exploration, disaster prevention, and tactical surveillance applications[1].

Because of the low propagation speed of acoustic signals (around 1500m/s), the propagation delay of acoustic signals is much longer than that of radio communication networks. Besides, data rates are very low due to the absorption, multipath and fading. Eventually, UANs usually suffer from high error probabilities because of error prone underwater acoustic channels as well as frequent changes in UAN topologies, which are caused by currents and tides[2]. Underwater communication equipment is powered by battery, which is power-limited and cannot be recharged. Consequently, it is essential to use battery efficiently. Under such circumstances, more reliable and higher throughput protocol for data transfer is highly required in UANs.

Network coding (NC) is proposed by Ahlswede et al.[3]. They demonstrate that by employing coding at the nodes, bandwidth can in general be saved. Katti et al. present analog network coding which exploits the interference to increase network capacity[4].

Network coding is a promising technique in terms of error recovery and throughput improvement in UANs. Moreover, analog network coding (ANC) has been demonstrated as an effective method of achieving remarkable throughput gains in multi-hop wireless network. The basic idea of ANC is to strategically make signals interfere at routers, afterwards routers forward the interfering signals instead of forwarding packets. The receiver leverages network-level information to cancel the interference, and recover the signal destined to it.

In this paper, we propose a Joint Linear-Analog Network Coding Based Protocol for Data Transfer in Underwater Acoustic Networks, LNC&ANC-MF for short. With this method, data transfer will be more reliable and the throughput will be higher. In LNC&ANC-MF, we build three disjoint paths first. Then six coded groups of packets (including three redundant groups of packets) are transferred from source to sink.

The organization of this paper is as follows. In Section II, we give the related work. In Section III, we develop a new network coding based protocol for data transfer. Numerical experiments are conducted in Section IV and conclusions are given in Section V.

II. Related works

A. VBF-NC

Vector Based Forwarding-Network Coding (VBF-NC) is a reliable data transfer scheme proposed by Guo et al.[5]. They show us how to achieve error recovery through NC in UANs. In VBF-NC, vector-based forwarding(VBF) is used to build multiple paths. Afterwards, network coded packets are delivered through the multiple paths. The disadvantage of this scheme is that VBF-NC only utilizes the error recovery function of network coding, but does not take advantage of the most significant feature of network coding, namely improvement of throughput.

B. MPNC

Multiple Paths and Network Coding (MPNC) , presented by Cai et al., improve the throughput[6]. Meanwhile they have a higher data delivery ratio and lower energy consumption in

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comparison with VBF-NC. Though MPNC perform well in UANs, there are some improvable aspects. One is to choose packets used for decoding selectively at relay nodes and sink node instead of random selection, which may cause decoding errors. The other one is to promote the usage of redundant packets when a node receives adequate packets for decoding. In MPNC, it assumes that nodes can decode successfully when they receive adequate packets. However, in this way, transferring redundant packets will waste network resources rather than improving reliability. The throughput has a great opportunity to be improved in UANs with multiple paths.

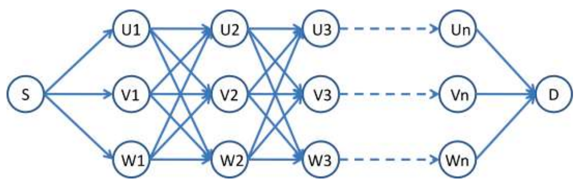

Fig. 1. network topology in LNC&ANC-MF

III. LNC&ANC-MF

In this work, one novel network coding based protocol for data transfer in UANs, called Linear Network Coding and Analog Network Coding based Multi-path Forwarding (LNC&ANC-MF) , is proposed to enhance the reliability and throughput in UANs.

In LNC&ANC-MF, as shown in Fig.1, a group of data packets needs to be transferred from the source node S to the sink node D over three disjoint paths, i.e., three relay nodes are in a relay set. For simplicity, we assume that it takes one time slot to transfer one packet from a node to the three nodes in its adjacent relay set. On account of the characteristic of ANC, we assume that each node in the UANs encodes packets with same linearly independent encoding vectors, which are chosen from a finite field F_{2^q} and stored in advance. We divide the packets to three sub groups with equal length, denoted as A, B and C . Taking A as an example, we divide it into generations, denoted as $A_1, A_2, \ldots, A_M$, with each containing K packets. Let $A_{11}, A_{12}, \ldots, A_{1K}$ be packets in the first generation. The source linearly combines each generation using encoding vectors. After network coding, A turns into $A'_{ij} = \sum_{k=1}^{K} h_{jk} A_{ik}$, where $i = 1, 2, ...M$,$j = 1, 2, ...P$ $P > K$,$k = 1, 2, ...K$. Then, B and C are operated like A respectively. Afterwards, the source XORs each two of them to get three sub groups of redundant packets D, E, and F ($D = A' \oplus B', E = B' \oplus C', F = A' \oplus C'$). Now, we have six coded sub groups of packets A', B', C', D, E and F at source, which have uniform subscripts. Next, network enters the stage of transmission, and S sends out $A'_{11}, \ldots, F_{11}, \ldots, A'_{MP}, \ldots, F_{MP}$ in sequence.

After detecting arrival of signal, nodes in relay one will do as the flow chart in Fig.2. Take an example of node U1. Firstly, U1 affirms whether signal received is interfered or not. If the signal is interfered, it will utilize ANC to separate and get the required packets. If not, it prepares for another reception.After finishing reception, U1 examines the number of receiving packets of the same generation. If the number is greater than K, it takes an underwater acoustic SNR estimation algorithm proposed by Wang et al. to select K packets with higher SNR[7]. If not, redundant packets are utilized to acquire the lost packets. However, it is uncertain that each bit is correct in a packet with higher SNR. In order to increase the role of redundant packets, we use a bit-by-bit comparison to get a new packet for decoding. Now U1 has enough and reliable packets for decoding. It decodes, recodes and broadcasts the new encoded packets.

Here we give detailed descriptions of some steps of operations mentioned above.

A. SNR estimation algorithm

Sampled signals are expressed as

$$y(k) = s(k) + \mathrm{k}(k) \tag{1}$$

where $\mathrm{k}(k)$ is a zero mean independent, complex gaussian random process, and satisfies

$$\mathrm{E}[\mathrm{k}(k)\mathrm{k}^{\mathrm{H}}(l)] = \mathrm{e}_n^2 \mathrm{W}_{kl} \tag{2}$$

where superscript H, e_n^2, and W_{kl} represent conjugate transpose, the noise power, and Kronecker function respectively. The received signal autocorrelation matrix is

$$\begin{aligned} \boldsymbol{R}_{yy} &= \mathrm{E}\{y(k)y(k)^{\mathrm{H}}\} \\ &= \mathrm{E}\{[s(k)+\mathrm{k}(k)][s(k)+\mathrm{k}(k)]^{\mathrm{H}}\} \\ &= \mathrm{E}\{s(k)s(k)^{\mathrm{H}}\} + \mathrm{E}\{\mathrm{k}(k)\mathrm{k}(k)^{\mathrm{H}}\} \\ &= \boldsymbol{R}_{ss} + \boldsymbol{R}_{\mathrm{kk}} \end{aligned} \tag{3}$$

It can be seen that the autocorrelation matrix of $y(k)$ is equal to the sum of the autocorrelation matrix of $s(k)$ and the autocorrelation matrix of $\mathrm{k}(k)$. Because of the nature of the autocorrelation matrix, $\boldsymbol{R}_{yy}$, $\boldsymbol{R}_{ss}$, and $\boldsymbol{R}_{\mathrm{kk}}$ are conjugate symmetric positive semidefinite matrixes. Eigenvalue decomposition is given as

$$\boldsymbol{R}_{ss} = \boldsymbol{Q} \Lambda_s \boldsymbol{Q}^{\mathrm{H}} \tag{4}$$

where $\Lambda_s = diag(\mathrm{V}_1, \mathrm{V}_2, \mathrm{V}_p, 0, ..., 0)_{m \times m}$ is a diagonal matrix, and the diagonal elements are the eigenvalues of $\boldsymbol{R}_{ss}$, which satisfy $\mathrm{V}_1 \geq \mathrm{V}_2 \geq ... \geq \mathrm{V}_\mathrm{p}$ and $p < m$. $\boldsymbol{Q}$ is an orthogonal matrix.

$$\boldsymbol{R}_{\mathrm{kk}} = \mathrm{W}_n^2 \boldsymbol{I} \tag{5}$$

where $\boldsymbol{I}$ is the identity matrix.

According to the equations (3), (4) and (5), we could have

$$\boldsymbol{R}_{yy} = \boldsymbol{R}_{ss} + \boldsymbol{R}_{\mathrm{kk}} = \boldsymbol{Q}(\Lambda_s + \mathrm{W}_n^2 \boldsymbol{I})\boldsymbol{Q}^{\mathrm{H}} = \boldsymbol{Q}(\Lambda_y)\boldsymbol{Q}^{\mathrm{H}} \tag{6}$$

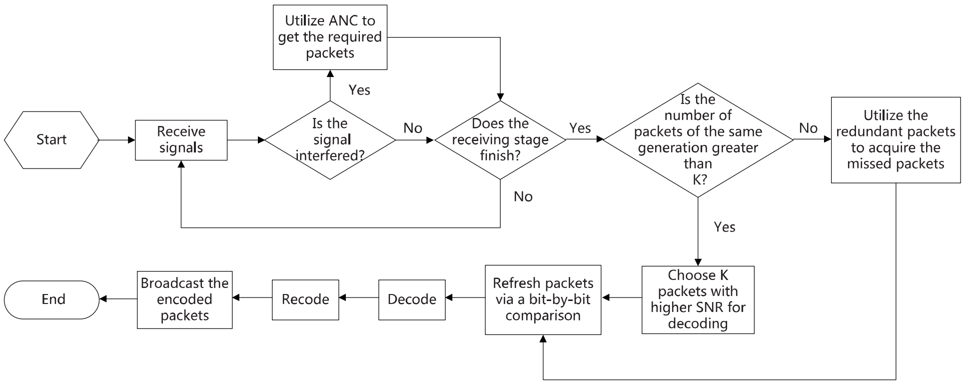

Fig. 2. Operations at relay nodes

where

$$\begin{aligned}\Lambda_y &= \mathrm{diag}(\lambda_1,\lambda_2,...,\lambda_m)_{m\times m} \\ &= \begin{pmatrix} \mathrm{V}_1 + \mathrm{e}_n^2 & & 0 \\ & \ddots & \\ 0 & & \mathrm{e}_n^2 \end{pmatrix}\end{aligned} \tag{7}$$

It can be proved that the power of signal $s(n)$ is the sum of singular values and the power of noise $\mathrm{k}(k)$ is $m\mathrm{e}_\mathrm{n}^2$. Therefore, the SNR of the received signal can be calculated through the following equation

$$SNR = 10\lg(P_s/P_n) = 10\lg\frac{\sum_{k=1}^{p}\lambda_k - \mathrm{e}_n^2}{m\times \mathrm{e}_n^2} \tag{8}$$

where p is the signal subspace dimension.

B. Bit-by-bit comparison

U1 XORs B'_{ij} and D_{ij} , C'_{ij} and F_{ij} to get another two packets about A'_{ij} , denoted as ${A'_{ij}}^1$ and ${A'_{ij}}^2$, where $i = 1,2,...,M$, $j = 1,2,...,P$. We compare every three bits at the same position of those three packets concerning A to refresh A'_{ij}. If the three bits are identical, U1 takes no action, else, U1 replaces the value of this position with the same value of the other two bits. After bit-by-bit comparison, a new A'_{ij} is obtained with high reliability.

C. ANC

Here we take an example to explain how ANC works in LNC&ANC-MF. After finishing decoding A'_1 , U2 uses the same encoding vectors to network code it. When U2 forwards A'_{11} to relay three, S forwards A'_{21} to relay one simultaneously. As a result, an intentional collision is occurred at the three nodes in relay one. U1 receives an interfered signal of $S_{A'_{11}}(t) + S_{A'_{21}}(t)$, and it can subtract $S_{A'_{11}}(t)$ corresponding to A'_{11} to get $S_{A'_{21}}(t)$, from which U1 can get A'_{21}. Obviously, the more hops are in the network, the more packets can be transmitted simultaneously. Hence, the throughput will be improved.

IV. Performance Evaluation

In this section, we employ successful delivery ratio (S-DR), normalized throughput (NT) and normalized energy consumption (NEC) to evaluate the performances of MPNC and LNC&ANC-MF.

Let the number of packets sent by the source node be F, the number of correct packets received by the sink node be U. SDR can be written as

$$R = U/F \tag{9}$$

NT is defined as

$$S = (FR)/T_{time} \tag{10}$$

where T_{time} is the total propagation delay time. In UANs, propagation delay time is the major component of the delay time and we only focus on the propagation delay time. For simplicity, we assume that it takes one time slot to transmit a packet in two adjacent nodes.

The power consumption parameters are in accordance with LinkQuest Underwater Acoustic Modems UWM1000, the power consumptions in the transmission, receiving and sleeping modes are 2 W, 0.75 W and 0.008 W, respectively[8]. In this paper, power consumption in the sleeping mode is negligible because it is concerned in the design of the MAC layer. Consequently, the energy consumption of a node can be expressed as

$$\begin{aligned}E &= E_{TX} + E_{RX} \\ &= FE_{txElec} + FE_{rxElec}\end{aligned} \tag{11}$$

where E_{txElec} and E_{rxElec} are the power consumption of receiving a packet and power consumption of transmitting a packet respectively. NEC is

$$T = \frac{\sum E}{RF} \tag{12}$$

Under the condition of low signal-to-noise ratio, the SDR of LNC&ANC-MF is much lower than that of MPNC. This

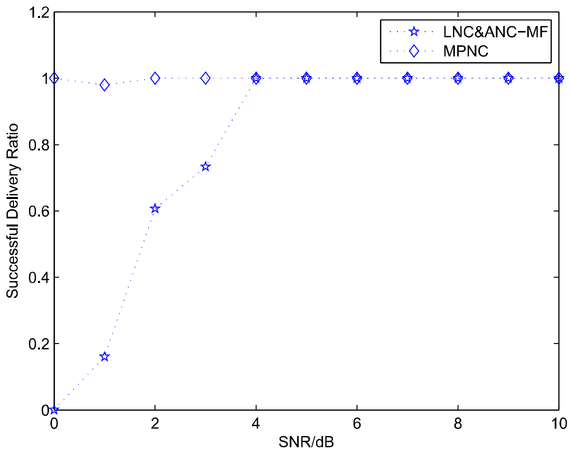

Fig. 3. Successful delivery ratio

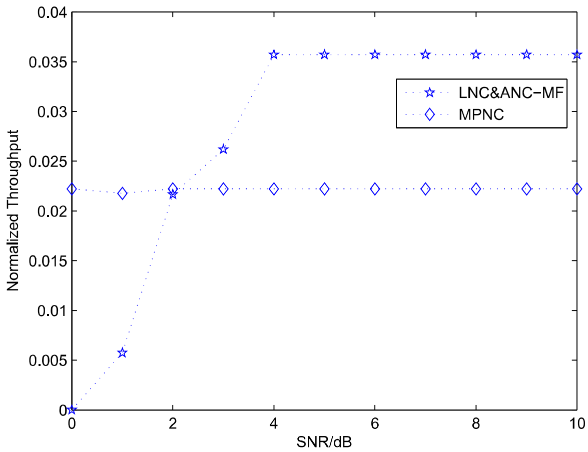

Fig. 5. Normalized throughput

is because of the introduction of ANC, which has high requirements for SNR. After the signal-to-noise ratio is greater than zero, the SDR of LNC&ANC-MF improves fast. When SNR reaches 4dB, LNC&ANC-MF performs as well as MPNC in SDR.

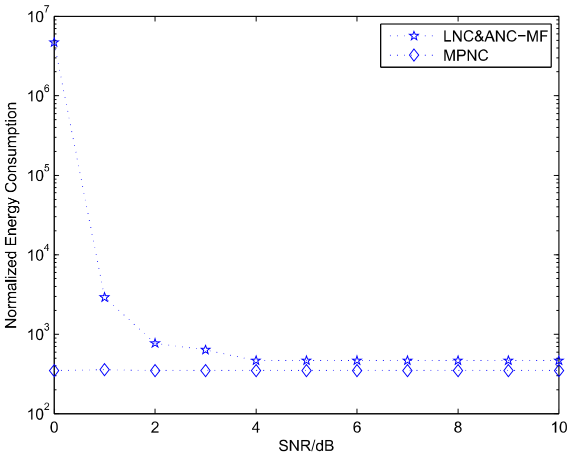

Fig. 4. Normalized energy consumption

In respect of NEC, LNC&ANC-MF consumes much more energy than MPNC when SNR is less than 4dB. However, with the increasement of SNR, the NEC of LNC&ANC-MF reduces rapidly. When SNR is greater than 4dB, the NEC of NC&ANC-MF is barely higher than that of MPNC.

In terms of NT, the two methods have basically equal NT when SNR is 2dB. When SNR is lower, LNC&ANC-MF needs more packets transmissions to ensure reliability, which consumes more power. When SNR is greater than 4dB, the NT of LNC&ANC-MF become stable is twice as high as that of MPNC.

In conclusion, on account of ANC, LNC&ANC-MF performs worse than MPNC when SNR is low. However, with SNR growing, the performance of LNC&ANC-MF improves rapidly. In steady state, SDR and NEC of LNC&ANC-MF are basically the same as those of MPNC, NT of LNC&ANC-MF is twice as that of MPNC.

V. Conclusion

In this paper, we propose a linear network coding and analog network coding based protocol for data transfer in underwater acoustic networks. For this protocol, higher reliability and higher throughput will be achieved in UANs. We believe that, for the sake of operability and practicability, this protocol is worthy of further investigation.

Acknowledgement

This work was supported by the Fundamental Research Funds for the Central Universities (3102015BJ015).

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