A Low Complexity Aggregation Method for Underwater On-Pipe Sensor Network

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ABSTRACT

This paper considers the sensor aggregation for underwater pipe-assisted stress wave communication (SWC). Although the SWC is able to support the on-pipe sensor network in short range, the spectrum of long-range SWC is limited due to the effect of reflections at the pipe joints. To address this issue, the orthogonal frequency-division multiplexing (OFDM)-based consensus data aggregation is proposed. Furthermore, the consensus data can be received via time-domain sampling after 'compute-during-transmit' in multiple access channels (MAC). The simulation results show 0.26%, 0.03%, and 0.08% mean-square-error (MSE) in 5, 10, and 20 sensor aggregation respectively with 5 dB average SNR. A vanishing mean-square-error (MSE) can be observed when increasing either the signal-to-noise ratio (SNR) or the number of sensors. This design can obtain the aggregated data by a simple time domain sampling with no need of down-conversion and demodulation.

KEYWORDS

Stress wave communications; wireless data aggregation; Internet of Underwater Things

ACM Reference Format:

Chenpei Huang*, Chaoxian Qi*, Aijun Song‡, Gangbing Song†, Jiefu Chen* and Miao Pan*. 2021. A Low Complexity Aggregation Method for Underwater On-Pipe Sensor Network. In *The 15th International Conference on Underwater Networks & Systems (WUWNet'21), November 22–24, 2021, Shenzhen, Guangdong, China.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3491315.3491343

1 INTRODUCTION

The stress wave communication (SWC) is one of the novel underwater communication methods assisted by the underwater pipe network. The unique advantage of SWC is its static and weakly attenuated channel, which allows longer communication range and higher data rate [2, 3, 5]. In those works, only a few pipe segments are considered and the experiments are performed in short-range SWC (S-SWC). However, regraded as long-range SWC (L-SWC) with tens to hundreds of joints, both the signal strength and bandwidth can be limited due to the existence the pipe joints between adjacent segments [4].

WUWNet'21, November 22–24, 2021, Shenzhen, Guangdong, China

ACM ISBN 978-1-4503-9562-5/21/11.
https://doi.org/10.1145/3491315.3491343

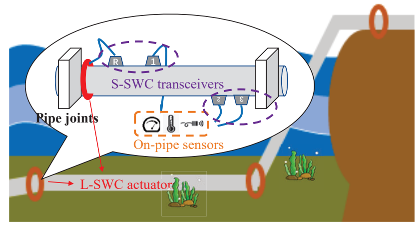


Figure 1: Underwater stress wave communication network.

In this paper, our proposed system shown in Fig. 1 addresses this problem. To prevent L-SWC from congestion, one can aggregate the data from on-pipe sensors via S-SWC, which significantly reduce the bandwidth usage of spectral limited L-SWC. Hence, a large on-pipe sensor network could be potentially accommodated. To this end, we propose an aggregation method to compute the consensus data during transmission in S-SWC multiple access channels (MAC). The OFDM precoding is also employed to spread the transmitted data into all subcarriers and match the S-SWC channels.

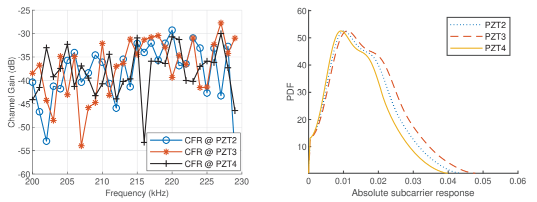
2 S-SWC CONSENSUS DATA AGGREGATION

2.1 "Through the pipe" Computation

We target at implementing a wideband, low-complexity aggregation in S-SWC on-pipe network. Inspired by AirComp [1] combining communication and computation, pipe communications work even better on signal-superposed aggregation due to the fading-free channel. In the following sections, we consider the uplink transmission of multiple sensors. While each sensor is equipped with a single transducer for S-SWC, a single-transducer relay can receive the aggregated S-SWC data and re-transmit via L-SWC. Without loss of generality, we also assume the arithmetic mean is the target function.

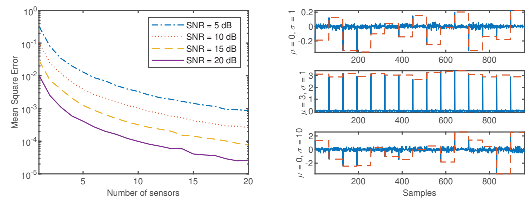
2.2 S-SWC Channel Characteristics

We build our testbed using cylindrical steel pipes with T-shape joint and random distributed PZT (Lead Zirconate Titanate) patches as the stress wave transducer. The channel response is highly frequency dependent in Fig. 2(a) because of the PZT deployments on the standing wave nodes or anti-nodes, which are determined by the wavelength and boundary conditions. Fortunately, if multiple subcarriers are considered, the distributions can be quite similar, as shown in Fig. 2(b). The slight difference might come from the tightness deviation when installing the PZT patches on the pipe wall. This observation indicates that a multi-carrier system (e.g., OFDM) provides near uniform sub-channel responses for multiple sensors, which is beneficial to the MAC function computing.



(a) Subcarrier channel gain (b) PDF of the sub-channel response

Figure 2: S-SWC channel response.



(a) Computation accuracy vs. SNR (b) Time domain signal @ 20 dB

Figure 3: S-SWC OFDM consensus aggregation.

As a result, we utilize a group of OFDM subcarriers for consensus aggregation instead of dissipating power on a certain frequency bottlenecked by the sensors located on anti-nodes. The fine channel estimation could be obtained by averaging multiple measurements before transmission thanks to the static channel. Regarding the synchronization, the time-reversal method can be adequate [2].

2.3 S-SWC OFDM Consensus Aggregation

Channel inversion is employed to compensate the phase shift and attenuation, which yields a uniform channel gain a^2 among users with power constraint P. The relay will calculate a^2 based on the previous estimated channel and then broadcast. By uniforming the target magnitude representing '1', the optimal gain and the corresponding OFDM precoder $\|\boldsymbol{C_i}\|_2 \leq 1$ are shown as:

$$(a^{opt})^2 = \min_i \boldsymbol{H_i}^H \boldsymbol{H_i}, \tag{1}$$

$$\boldsymbol{C_i} = \frac{\boldsymbol{H_i}^*}{\boldsymbol{H_i}^H \boldsymbol{H_i}} a^{opt}, \tag{2}$$

where $\boldsymbol{H_i}, \boldsymbol{C_i} \in \mathbb{C}^{N\times 1}$ denote the ith sensor subcarrier response vector and precoder, respectively. $(\cdot)^H$ means conjugate transpose. We then notice that the estimated aggregated data equals to the sum over receiving OFDM subcarriers, represented as:

$$\tilde{g} = \frac{1}{Ka^{opt}\sqrt{P}} (\sum_{i=1}^{K} \boldsymbol{C_i}^T \boldsymbol{H_i} \sqrt{P} x_i + n), \tag{3}$$

where $\tilde{g}$ denotes the target arithmetic mean and n is the receiver's thermal noise. $(\cdot)^T$ means the matrix transpose. Following inverse Fast Fourier Transform, the desired sum in the bracket in Eq. (3) is the first sampling scaled by a constant in the time domain.

3 SIMULATION AND DISCUSSION

We select 200 kHz to 206.4 kHz for demonstration. The overall bandwidth is 6.4 kHz divided by 64 orthogonal subcarriers. Consequently, the sampling frequency is set as 12.8 kHz. Multiple sensor channel responses are generated from the testbed measured distribution in Fig. 2(b).

We first evaluate the computational accuracy by calculating the mean-square error (MSE) assuming sources are standard normal distributed. We demonstrate the impact of SNR and the emitter number in Fig. 3(a). When the SNR is 5 dB, the simulated MSE (averaged from 1000 trials) are 0.26%, 0.03%, and 0.08% in 5, 10, and 20 sensor cases, respectively. Also, the MSE will vanish as the increment of the SNR since the noise term in (3) is suppressed. We also notice an "aggregation gain". This is because the coherent and concurrent transmission is similar to beamforming. Consequently, the transmission power can be lowered down without losing significant accuracy.

In Fig. 3(b), we show the receiving signals (CP-removed) with 20 dB SNR in solid line and the desired data in dashed line. The period of one aggregation is 64 samples. We notice the first sample of the received signal is the estimated consensus without extra down-converting or coherent detection modules. In the second and third subplots in Fig. 3(b), we can also observe the valid data is distinguishable from the noise-like floor when the mean and variance become larger. This property can be used to determine the reliability of aggregated results.

4 CONCLUSION

In this paper, we address the consensus data aggregation in underwater on-pipe sensor networks. Based on the signal superposition property, we propose a wideband aggregation using OFDM precoders to fit the S-SWC channel with non-flat frequency response. The simulation results suggest the computation accuracy could be improved either the SNR or sensor population increases. Without down-converting and demodulation, a simple time-domain sampling is sufficient to determine the consensus data, which can significantly reduce the cost and complexity.

ACKNOWLEDGMENTS

The work of C. Huang, C. Qi, G. Song, J. Chen, and M. Pan was supported in part by the Department of the Treasury through the State of Texas under the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act of 2012 (RESTORE Act). The work of C. Huang, C. Qi, J. Chen, G. Song and M. Pan was also supported in part by the U.S. National Science Foundation under grant CNS-1801925.

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