A Parallel Decoding Approach for Mitigating Near-Far Problems in Underwater Acoustic Communications Networks

Yuehai Zhou, Feng Tong, and Roee Diamant

***Abstract*—A limiting factor of communication networks is the so-called near-far effect, where transmissions from a node (near) close to a common receiver blocks transmissions of a farther node (far). Due to the high power attenuation in the underwater acoustic channel, near-far is common in underwater acoustic communication networks (UWANs), and the phenomena occurs even for a rate of 1/2 between the distances of the near and far nodes to the receiver. In this paper, we offer a novel interference cancellation (IC) approach for handling such interference by decoding the ”near” signal and the ”far” one in parallel, thereby improving detection for both signals. Simulation results show that, compared to the traditional decision feedback equalizer, our approach gains 12 dB in the output SNR of the jammed source and 4 dB in the output SNR of the jamming source.**

***Index Terms*—Underwater acoustic communications, near-far, interference cancellation, compresive sensing**

I. Introduction

With the boost of underwater acoustic communication (UAC) capabilities, multitude of applications started using this technologies. Among these, are settings involved multiple transmitting nodes such as for oceanographic data collection, communication between autonomous submerged vehicles, and group of scuba divers performing subsea maintenance [1]. A common challenge in these applications is how to deal with joint interferences from signals received simultaneously by a common receiver. Since the bandwidth in UAC is highly limited, the data rate is extremely low, and reception is mostly performed omni-diretional (i.e., no directivity is applied in reception), interfering signals cause collisions and loss of data.

In this paper, we focus on the so-called *near-far* problem, where colliding packets may be resolved for a source located close to the receiver, but for the farther node, the signal-to-interference ratio (SIR) is high. Here, the closer source is often called the *jamming* node while the farther node is called the *jammed* node. In UAC, due to the high dependency of the power attenuation in range both for propagation loss and absorption loss, the near-far problem exists even for range ratio of half between the jamming-receiver range and the jammed-receiver range.

While in some cases, near-far situations cause diversity and thus can be viewed as a network resource to assist network operations [2], [3], commonly, this phenomena is regarded as a source of interference that should be resolved either in the MAC layer or in the Physical layer of the communications stack. In the context of MAC scheduling, the near-far problem is viewed as a source for secondary conflicts [4], for which the network should avoid in the first place. The solution thus involves identifying a near-far scenario as part of the process of topology-discovery. In [5] near-far situations are identified by non-symmetric components in the network topology matrix, which basically mean that there is a jammed node in the network. In [6] near-far collisions are identified by the common receiver based on parts of the signals that do not collide. This approach is practical since, due to the long propagation delay in UAC, there is a very low chance for completely overlapping receptions. In [7] expected near-far collisions are identified prior to transmissions based on acoustic propagation models, assuming location knowledge of the nodes. Once a near-far is identified, the scheduling solution is altered by setting proper constraints for the selected transmission schedule such that the jamming and jammed nodes avoid transmitting together [8], or the near node is instructed to adjust its power to avoid the jamming altogether [9].

In the context of the Physical layer, near-far situations are solved through filtering. The most common is the noise-canceling filter, where the strong signal is first resolved and then removed from the received signal to allow the decoding of the jammed signal. To that end, a synthetic version of the resolved strong signal is used as a reference, which passes through a filter and is then subtracted from the received signal. The filter adapts by minimizing the output of the noise cancellation filter [10]. For UAC, in [11] this approach has been extended to direct the adaptive filter to identify only the strong signal, thereby reducing the effect on the jammed signal. Multiuser interference suppression has also been applied in the context of equalization, where interferences are treated as residuals from the channel estimation process [12], by iteratively resolving inter-block interferences [13], or by means of interference alignments [14]. In all these cases, the decoding is performed sequentially under the assumption that the jamming signal can be correctly resolved. While this be true in some cases, mostly the near-far situation is not conclusive, meaning that the jamming signal is also being interfered.

Different than current approaches that perform the interference cancellation (IC) sequentially, our approach performs the decoding on parallel. This not just offers benefit in terms of

Yuehai Zhou and Roee Diamant are with the Hatter Department of Marine Technology, University of Haifa, Haifa 3498838, Israel; Feng Tong is with the Key Laboratory of Underwater Acoustic Communication and Marine Information Technology of the Ministry of Education, Xiamen University, Xiamen, Fujian 361005, China.

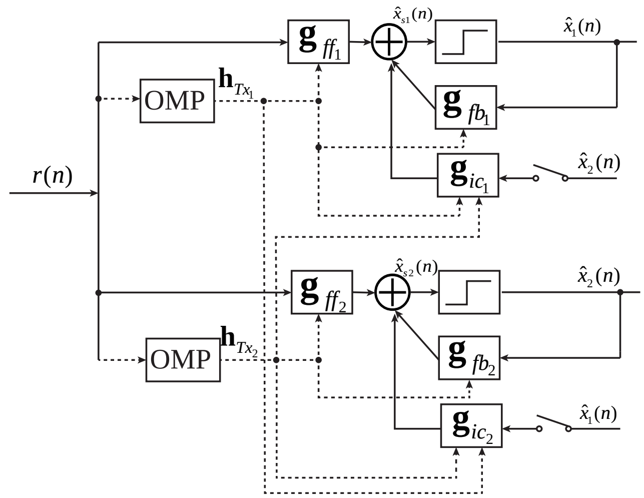


Fig. 1: The IC DFE scheme.

latency, but also allows better decoding of the near signal. Our method works by combining the IC operation within the decoding process of the two source-decoding branches in the framework of a decision feedback equalization (DFE). The IC operation exploits the spatial sparsity between the two near-receiver and far-receiver channels through a compressed sensing algorithm. Inside the source-decoding branch, this allows enhancing channel estimates with common delays, thus coming from the desired transmitter, and to suppress channel taps with different delays assumed coming from the other transmitter. In particular, the cancellation is performed in parallel to the feedback filter and by sharing the outputs of the feedback filter. The forward process adds positive channel taps to the support set of the equalizer, while the backward process removes those designated to the interference.

Our contribution is in the design of an IC-based approach for resolving the near-far problem for cases where the emissions of the near source are also affected by those of the far source. We analyze the performance of our algorithm in numerical simulations and demonstrate its practicality for a realistic sea environment in a designated sea experiment. Compared to the traditional DFE, the results show that our proposed method obtains higher output SNR.

II. The Joint IC method

We demonstrate our IC approach in the framework of a decision feedback equalizer (DFE). To facilitate simultaneous decoding of both the jammer and jammed signals, we execute two DFE branches in parallel. Yet, assuming the jammer-receiver and the jammed-receiver links are significantly different, each DFE is fed by its own channel estimator. For the later, we use the orthogonal matching pursuit (OMP) algorithm [15]. We use the OMP due to its compressed sensing application, which is specifically suitable for the case of two colliding signals that needs to be separated.

In essence, the IC operation is similar to the removal of residual channel estimation noises in the DFE scheme. Hence, as illustrated in Fig. 1, we operate the IC in parallel to the feedback filter of each DFE branch. Similar to the feedback filter, the IC draws its input from the symbol's hard decision. However, different than the feedback filter, this decision is taken from the second DFE branch. As a result, the IC is set to remove residuals of noises from the other channel. To that end, we note that such removal is possible only upon existence of an interference. In other words, only when there is in fact a hard decision output from the second DFE branch. We illustrate this operation in Fig. 1 by the switch at the entrance to the IC. This switch comes to combat the practical case of partial colliding between communication packets.

Much like the feedback filter, the IC is an adaptive filter. The IC filter is designed to mitigate interference from a different source. As such, referring to Fig. 1, the parameters of the filter are set by the estimated channel from the other DFE branch (the OMP block). Yet, since the IC for channel j is operated after the feed-forward filter of channel j, which in turn is set by the channel equalization for channel j, also channel j should be considered to set the parameters of IC i.

III. Simulation Results

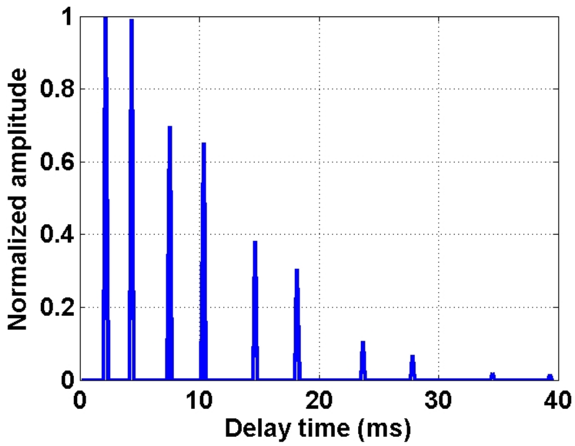
In this section, we describe results of our parallel IC approach in numerical simulation.

A. Setup

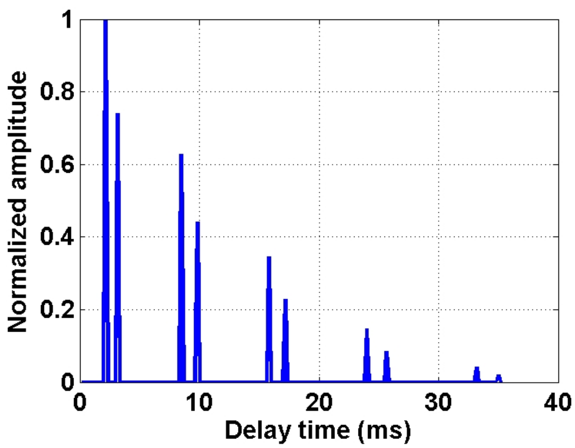
Our setup includes three nodes, a receiver array which contains four receiving elements and two transmitters. For each Monte-Carlo simulation run, the location of one of the transmitters is fixed at 1000 m from the receiver, while the location of the second transmitter is chosen uniformly randomly such that its range from the receiver is between 2000 m and 100 m. The depth of the 4 receiving elements is 4 m, 8 m, 12 m, and 16 m, respectively, the depth of the transmitters is fixed at 8 m. The two sources transmit equal packets of 134320 bits within the same frequency band and the same symbol rate at 6000 symbols/s. The packets are scheduled such that overlapping always occur.

To generate the propagation delay and channel impulse response for the jamming-receiver and jammed-receiver links, we use the Bellhop ray-tracing software package [16]. A flat ocean is assumed with a constant sound speed profile at 1500 m/s and a constant water depth of 20 m. For each location setup, the transmitted signals are convoluted with the corresponding channel, while for the latter we pick the 10 most dominant rays. An example for two such channels is shown in Fig. 2 for two transmitters located 1000 m and 500 m from the common receiver. In this example, the delay spread is roughly 40 ms, and a typical sparse nature is observed.

To benchmark our scheme, we use two channel estimation based decision feedback equalizers (DFE). The first, denoted as *DFE-IC*, removes interference, while the second, denoted as *DFE-NIC*, does not. In both cases, channel equalization



(a)



(b)

Fig. 2: Example of two simulated channels. Upper panel: 500 m range, 8 m depth. Lower panel: 1000 m range, 16 m depth.

is based on the OMP algorithm and a designated training sequence.

B. Results

To measure performance, we use the output signal-to-noise ratio (SNR) metric. The output SNR is measured at the input of the decision-making block and is defined by

$$\rho = \frac{\|\mathbf{x}\|_2^2}{\|\mathbf{x} - \bar{\mathbf{x}}\|_2^2} \,, \tag{1}$$

where $\boldsymbol{x}$ is the transmitted symbols, and $\bar{\boldsymbol{x}}$ is the soft output from the receiver. The range vs. output SNR is shown in Fig. 3 for the *fixed* node at 1000 m range and for the *varied* node. As expected, when the varied node is closer, it obtained higher output SNR since it experiences less interference from the fixed source. Similarly, high output SNR is measured for the signal obtained from the fixed transmitter when the varied transmitter is far. Comparing the DFE-IC and DFE-NIC schemes, we observe that higher output SNR is obtained by the former.

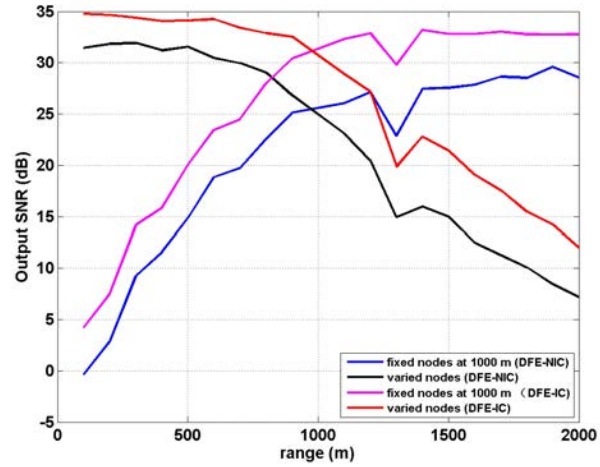


Fig. 3: Output SNR as a function of range of the varied source. SNR=30 dB.

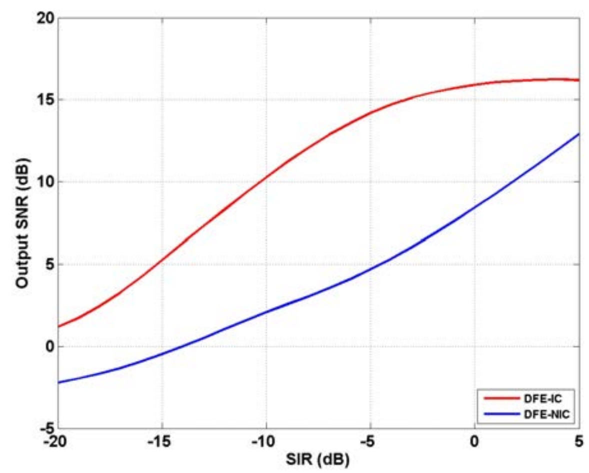


Fig. 4: SIR vs. Output SNR. SNR=30 dB.

Another measure of interest is the signal-to-interference ratio (SIR), defined by

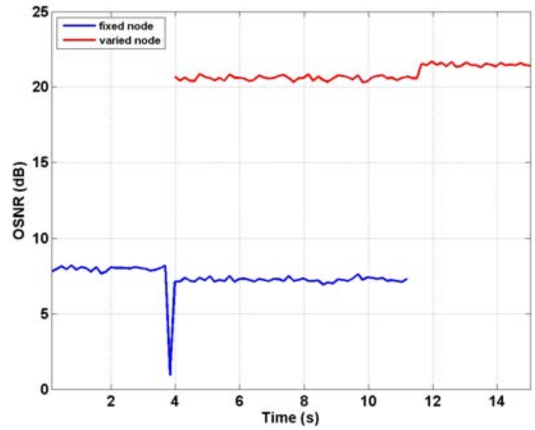
$$\rho = \frac{\|\boldsymbol{s}\|_2^2}{\|\boldsymbol{r}\|_2^2} \,, \tag{2}$$

where $\boldsymbol{s}$ is the desired signal, and $\boldsymbol{r}$ is the interfering signal. In Fig. 4, we show the SIR as a function of the output SNR in the training mode. Here, the signal from the transmitter at the 1000 m range is considered the desired signal, while the signal from the varied node, this time at 500 m from the receiver, is the interefering one. For a fair comparison, the two channels are normalized. We observe that output SNR increases with the SIR. This is because, the less interference the better the decoding process. In this respect, we observe a gap of 3 dB in favour of DFE-IC.

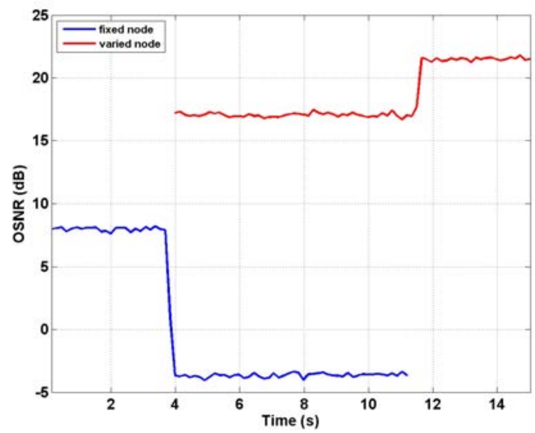
Another interesting performance exploration is the behaviour of the decoder for the practical case where the two signals do not collide perfectly. In this case, if the time of interference-free channel is identified well, a valid approach would be to operate DFE-IC at times when interference exists, and use DFE-NIC when the channel is interference-free. Adopting this approach, Fig. 5 shows the output SNR for the case where only signals from the fixed node arrive at the first 4 s of reception; collision occurs between time 4 s and 11.2 s; and then only signals from the varied node exist. The upper panel shows the results of the combine scheme, while the lower panel shows the results for only DFE-NIC. Looking at the results in Fig. 5b, we observe that when a collision occurs, the output SNR for DFE-NIC drops by roughly 13 dB for the jammed (far) source and by 5 dB for the jamming (near) source. However, in Fig. 5a, when IC is used, a reduction of only 1 dB is observed for the jammed and jamming sources. That is, the gain obtained is 12 dB for the jammed source, and 4 dB for the jamming source.

IV. Conclusions

In this paper, we considered the problem of near-far in the setting of an underwater acoustic communication sensor network, where packets from a near source collide with that of a far source. Different than common approaches that assume perfect decoding of the jamming signal and thus perform interference cancellation (IC) sequentially, our approach is based on a parallel decoding of the near and far signals. This approach holds the benefits of lower latency, but more importantly, as we showed in numerical simulations, higher output SNR is obtained both for the jammed signal and jamming signal. Further, we proposed a combined approach to perform non-IC when no interference exists, and IC when collisions occur. Our results showed a gain of 12 dB in the output SNR of the jammed source and 4 dB in the output SNR of the jamming source. Further work will exploit the channel differences between the near and far nodes for IC, and will prove the validity of our approach in a sea experiment.



(a)



(b)

Fig. 5: Output SNR as a function of time for the case of partial collision. Upper panel: use of a combination of DFE-IC and DFE-NIC. Lower panel: use of DFE-NIC only.

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