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A novel polar-coded multipath-cluster-alignment receiver for high-data-rate long-range deep-sea acoustic communications

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High-data-rate, long-range acoustic communication, as a frontier technology for deep-sea technical applications, has drawn considerable attention due to growing demand for information transmission among diverse underwater terminals over large deep-sea dimensions. However, the large multipath spread, random time variations, and low signal-to-noise ratio (SNR) associated with long-range deep-sea acoustic channels pose significant challenges [1]. Although channel equalization techniques have been explored to mitigate these issues, their performance degrades severely in channels with low SNR and large delay spread, thereby limiting the effectiveness of conventional adaptive equalization algorithms.

The inherent sparsity and large inter-cluster delay of deep-sea acoustic channels present an opportunity to exploit the separability and diversity of the multipath clusters (MCs). Previous investigations employing multiple-element receiving arrays [2,3] and high-order multichannel adaptive equalizers managed to achieve high-data-rate long-range performance; however, it has been observed that they lead to rapid increase in complexity, making them unsuitable for smart underwater terminals like autonomous underwater vehicles, subsurface buoys or other deploy-able internet of underwater things nodes, which are typically equipped with limited computational resources and a small number (one or two) receiving elements.

Polar coding [4], a promising solution in 6G and ultra-reliable low-latency communication, offers potential for high-throughput, low-complexity systems. However, its application in deep-sea scenarios is severely affected by low input SNR and multipath uncertainty, as it requires relatively high SNR and reliable channel performance. In [5], we proposed a spatial-temporal joint equalizer to explore spatial-temporal sparsity and MC diversity for a polar-coded receiver, so that deep-sea communication using two receiving elements with a peak data rate of 6000 bps can be achieved at a distance of 20 km, under an input SNR of approximately 10 dB. By decomposing the equalization of a large spread deep-sea channel into a weighted combination of aligned outputs of multiple MC sub-equalizers and using a Lagrange multiplier, coefficients and weights could be optimized iteratively. However, the lack of a rigorous theoretical foundation degrades the performance of the nonlinear optimization process in [5] at lower SNRs. This is because its coupled, non-convex formulation becomes highly susceptible to local minima under noisy conditions, thus limiting its applicability to longer transmission ranges. Here, the proposed joint iterative approach can enhance the low-SNR performance by decomposing the problem into modular, well-posed linear sub-tasks that are inherently more robust to noise and initialization.

For long-range deep-sea acoustic communication within the framework of MC joint equalization, we proposed a novel polar-coded MC-alignment receiver consisting of an MC-alignment equalizer and a polar encoder/decoder. This equalizer can adopt joint iteration of multiple aligned MC sub-equalizers, avoiding nonlinear optimization. This design can help a polar coding receiver yield long-range communication over lower SNR.

Multipath-cluster-alignment equalization. Consider a single-input multiple-output (SIMO) deep-sea acoustic communication system, as described in detail in Appendix A. For the large spread channel $h_m(n)$ as a whole, a high-order, high-complexity equalizer would generally be required. This is because the delay spread in each MC is significantly smaller, and this helps the high-order equalizer to decompose into K sub-equalizers. Each of them addresses an individual MC in parallel by aligning its input to the corresponding MC (see Figure 1).

Specifically, MCs in the channel $h_m(n)$ are extracted by identifying the most prominent K peaks. The delay $\tau_{m,k}$ for each MC is calculated by cross-correlating the received signal and the known preamble. Aligning the k-th MC with $\tau_{m,k}$, the input to the k-th sub-equalizer is calculated from the contribution of the aligned k-th MC and the other non-aligned MCs, through the following equation:

$$\begin{aligned}
y^{\mathrm{al}}_{m,k}(n) &= y_m(n) * \delta(n+\tau_{m,k}) \\
&= \{s(n) * h_m(n) + v_m(n)\} * \delta(n+\tau_{m,k}) \\
&= s(n) * h^{\mathrm{al}}_{m,k}(n) + \sum_{i=1,i\neq k}^{K} s(n+\tau_{m,k}) * h_{m,i}(n)
\end{aligned}$$

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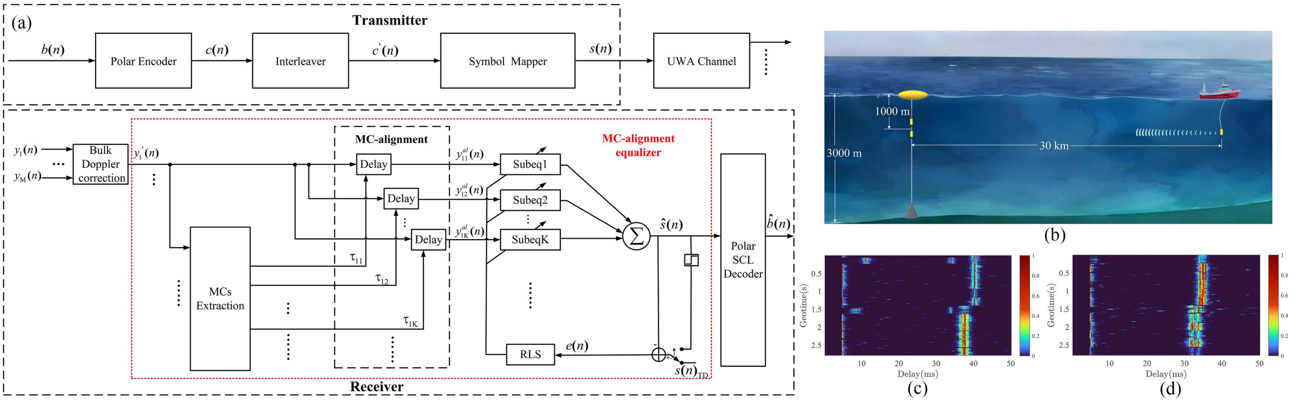

Figure 1 (Color online) The proposed polar-coded MC-alignment receiver. (a) The proposed polar-coded MC-alignment receiver. (b) Diagram of the sea trial. Channel estimation result of (c) receiving element 1 and (d) receiving element 2.

$$\begin{aligned} &+ v_m(n+\tau_{m,k}) \\ &= s(n) * h^{\mathrm{al}}_{m,k}(n) + v'_{m,k}(n), \end{aligned} \tag{1}$$

where "*" represents the convolution operation, $h^{\mathrm{al}}_{m,k}(n)$ denotes the aligned CIR (channel impulse response) of the k-th MC, and $v'_{m,k}(n)$ is the ISI (inter-symbol interference) from other MCs, which can be assumed to be independent additive noise. This is because the delay between adjacent MCs is larger than the order of sub-equalizers itself in the typical deep-sea channels, with variance $\sigma^2_{v'} \approx \sigma^2_v + \sum_{i=1,i\neq k}^{K} \sum_{l=0}^{L_i-1} |a_{m,i,l}|^2$. Thus, the weight coefficients of each sub-equalizer could be iteratively optimized by using mainstream adaptive algorithms, such as the recursive least squares algorithm, by minimizing the corresponding error function between the known training sequence and the combined output of all sub-equalizers along m and k, as discussed in Appendix A.

Furthermore, complexity and OSNR (output signal-to-noise ratio) performance analysis, as discussed in Appendix A, reveal that performance enhancement of the proposed equalizer depends on the total number of MCs used in the MC-alignment. In other words, MCs in deep-sea channels enhance the effect of MC diversity exploration, with a small number of receiving elements and a short training sequence for sub-equalizers. Moreover, the processing gain achieved by MC-alignment equalization also enables the adoption of high code rate polar encoding, which otherwise needs a high effective SNR precondition.

Deep-sea field test. As illustrated in Figure 1(b), data collected from a 30 km deep-sea acoustic communication experiment conducted in the South China Sea is used to evaluate the performance of the proposed receiver with a polar coding/decoding scheme (refer to Appendix B for details) and the MC-alignment equalizer. The specific parameters of this communication system consisting of a transmitter with a source level of approximate 190 dB re 1uPa@1m suspended at a depth of 1000 m and a two-element receiving array with the upper and the lower hydrophone deployed at a depth of 950 and 1050 m, respectively, are provided in Appendix C.

Figures 1(c) and (d) show a typical clustered multipath pattern of the measured CIR of two receiving elements, each of which contains two well-separated MCs with average SNR values of 3.08 and 1.71 dB, respectively.

The specific parameters and compared results of the reference mainstream receivers are summarized in Appendix C. The proposed receiver achieved 12-frame error-free performance after polar decoding, whereas the reference mainstream receivers failed to achieve the same, even with polar decoding.

Conclusion. In this study, we proposed a novel receiver by incorporating the concept of MC-alignment equalization with polar coding for high-data-rate long-range deep-sea acoustic communication. The proposed scheme used two receiving elements and achieved error-free communication over a horizontal distance of 30 km in the South China Sea. This attains a peak data rate of 4000 bps, corresponding to an effective data rate of 3644.1 bps, under an SNR of <3 dB.

To the best of our knowledge, this performance surpassed the previously reported SIMO investigations in terms of data rate/distance product, the element number and the received SNR, thus emerging as a potential scheme in the field of information transmission in diverse deep-sea environments.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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