How Much Information Can Be Stored Using Very Short Molecules?

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Abstract

From an information-theoretic point of view, the commonly adopted DNA storage channel, the shuffling-sampling channel, has two distinct operational regimes. If the stored molecules are relatively long, so that the number of molecule types is larger than the number of molecules storing the message, the channel capacity is positive. Alternatively, if the molecules are relatively short and so that the number of molecule types is smaller than the number of molecules, then the resulting storage system is characterized by zero capacity. In this short molecule regime, Shomorony and Heckel (2022) put forward a conjecture on the scaling of the number of information bits that can be reliably stored. While this conjecture was partially proved by Gerzon, Weinberger, and Shomorony (2025), we complete the proof of this conjecture. We analyze a random-coding scheme in which each codeword is obtained by rounding a randomly chosen point from the probability simplex. By analyzing the optimal maximum-likelihood decoder, we derive an achievability bound that matches the recently established converse bound across the entire short-molecule regime. Since the random-coding scheme is computationally heavy, we also propose an alternative coding scheme that operates at a significantly lower computational complexity but achieves the optimal scaling, except for a specific range of very short molecules.