A Chemical Reaction Network for Successive Interference Cancellation in Molecular Communication Networks

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Abstract

In this work, we conduct a preliminary evaluation of a chemical reaction network (CRN) realizing the successive interference cancellation (SIC) algorithm. SIC is a signal processing method used, for example, in non-orthogonal multiple access schemes. We present a CRN design with the sampled molecule concentration as the input and the detected bits as the output in a system with two transmitters and one receiver and evaluate its performance via stochastic simulations. This is a step towards realistically modeling SIC and possible effects on algorithm design in the chemical domain.

Keywords

chemical reaction network, successive interference cancellation

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1 Introduction and Background

In a future internet of bio-nano-things (IoBNT), molecular communication (MC) could enable connectivity between many low-capability nano-scale devices for novel bio-medical use cases. Previous work on, for example, modulation, coding or multiple access (MA) techniques, proposed different algorithms, often without considering their implementation in a biological system. Recently, chemical reaction networks (CRNs) have gained popularity in the MC field as a possible substrate for biological computations based on molecular inputs and outputs and a way of modeling corresponding limitations [2, 4]. In this work, we focus on successive interference cancellation (SIC) as an algorithm necessary to implement a non-orthogonal multiple access (NOMA) technique based on the number of received molecules [5]. A CRN design is presented implementing an approximation of a SIC algorithm with several simultaneous chemical reaction blocks to generate the output bits of a two-transmitter (TX) system. We discuss our choice of reaction rate constants, evaluate the performance of the CRN both using deterministic ordinary differential equation (ODE) solvers as well as particle-based stochastic simulation and discuss the impact and implications for an exemplary NOMA communication scenario.

Our analysis is based on the scenario presented in [6], where 2 TXs communicate with a single spherical receiver (RX) over a free diffusion channel. The system implements NOMA using SIC and we use a stochastic Poisson channel model [3]. Based on the parameter choices taken in [6], we set the diffusion coefficient $D = 10^{-9}\,\mathrm{m^2\,s^{-1}}$, RX radius $r = 1\,\mu\mathrm{m}$, TX–RX distance $d = 10\,\mu\mathrm{m}$, and the molecule budget per symbol per TX $N_{\mathrm{TX,max}} = 10^6$. The received signal is the sum of the signals from all TXs since they use the same molecule type and transmit simultaneously. For this analysis, we assume each TX transmits a single bit using on-off-keying, with the number of emitted molecules per bit-1 pulse from each TX being $N_{\mathrm{TX},1}, N_{\mathrm{TX},2} < N_{\mathrm{TX,max}}$. We utilize the SIC model as described in [6]: we sample the received number of molecules at the signal peak and compare with threshold τ_1, decoding either 1 or 0 for TX_1, if the sample is larger or smaller, respectively. Based on this, we choose one of two thresholds for TX_2, τ_2^1 or τ_2^0, and compare it with the same peak sample to decide for a 0 or 1 for TX_2. It is possible to analytically find the optimal thresholds as well as the optimal number of emitted molecules or approximate them via a pilot-symbol-based protocol [5, 6]. Therefore, we assume we have knowledge of those optimal values.

2 Chemical Reaction Network Design

We have designed a CRN structure that takes the sampled molecule concentration as an input and returns the detected bits via two different indicator molecule species for each TX_i, D_i^0 and D_i^1. The larger of both output values determines the detection of a 0 or a 1. The computation is split into several blocks of operations like comparisons and additions as defined in [4]. Each block is defined by input and output species as well as a reaction rate constant κ determining the reaction speed. Different blocks are coupled via shared inputs and outputs. We assume a unit-less time axis and that all reaction rate constants are normalized relative to the maximum 1. The reaction blocks are as follows and as in Figure 1:

(1) Comparison: compare sampled concentration Y_{on} with threshold concentration of species W_1 (representing τ_1). The result is stored in the ratio of two species X_{on} and X_{off}.
(2) Translation: translate X_{on} and X_{off} species into new detection species to decouple the comparison from the detection.
(3) Approximate majority: Creates binary decision by turning an input ratio $D_1^j/D_1^k > 1$ with a small surplus of any species into an output ratio $D_1^j/D_1^k \gg 1$.
(4) Threshold adaptation: Add the resulting number of D_1^1 molecules to a baseline threshold $W_{2,\mathrm{B}} (= \tau_2^0)$ for TX_2. The values are tuned such that $(\tau_2^1 =) W_2 = W_{2,\mathrm{B}} + D_1^1$.
(5) Repeat steps 1–3 for TX_2 to determine the resulting bit via D_2^0 and D_2^1

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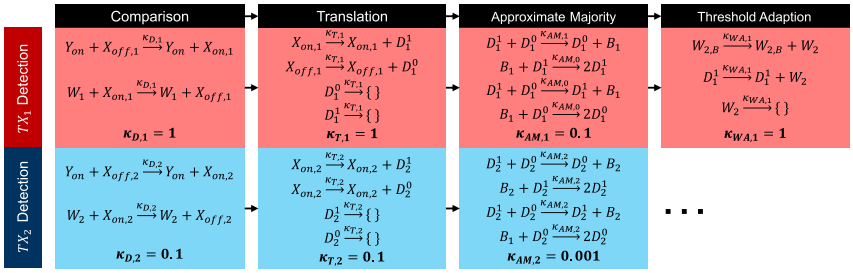

Figure 1: Proposed structure of a CRN implementing a two-stage SIC algorithm on the RX side. Global input: Y_{on}, ouputs: D_i^0, D_i^1

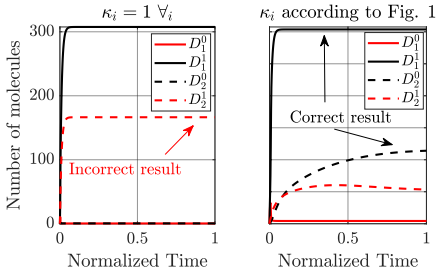

Figure 2: Comparison of two different choices of reaction rate constants κ_i. The desired result is for D_1^1 and D_2^0 (in black) to be in the majority.

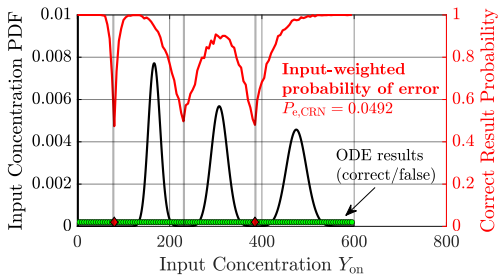

Figure 3: CRN evaluation using ODE solvers (binary result: green/red) and stochastic simulation (probability of error).

Now we are left with choosing the reaction rate constant values, i.e. $\kappa_{\text{D},i}, \kappa_{\text{T},i}, \kappa_{\text{AM},i}, \kappa_{\text{WA},1}$, as defined in Figure 1. As space will be severely limited in future IoBNT nodes, we assume that all the reactions take place concurrently within a single reaction volume. This removes the need for separate enclosed spaces for each reaction block or for the two TX decoding steps. Therefore, our goal is to intuitively design the reactions such that they naturally produce results in the correct order, as strict optimization is beyond the scope of this paper. This is primarily determined by the ratio between the reaction rate constants. We choose the values as specified in Figure 1. Figure 2 shows an example result for the detection species D_i^j using an ODE solver. The input is such that D_1^1 and D_2^0 should be the dominating species. On the left, all κ are equal to 1 and we see that this yields an incorrect result. D_2^1 dominates because the second comparison block reacts too quickly to the non-adapted incorrect threshold. Our choice of κ on the right side corrects the initial rise of D_2^1 and yields the correct result.

3 Evaluation and Conclusion

Given our scenario, the inputs Y_{on} are distributed according to 4 Poisson distributions with different means corresponding to the 4 possible bit combinations sent by TX_1 and TX_2. Figure 3 depicts the results for both the ODE analysis indicated by the correct (green) or incorrect (red) markers at the bottom, and the stochastic simulations using Gillespie's algorithm [1] as a probability across 1000 realizations. To determine the impact on the system performance, the error probability must be weighted by the input likelihood. A crucial observation is that the error probability is roughly inverse to the input likelihood, mitigating the impact of high error probabilities around the thresholds. The combined result is shown in the figure as the total CRN error probability. $P_{\text{e,CRN}} = 0.0492$. We note, that while relatively manageable this is several orders of magnitude higher than the inherent error probability of the system as calculated in [5]. Therefore, it is likely that a lot of the performance optimization potential lies with the chemical implementation as opposed to the communication system itself. Tuning real-life reaction speed, the search for practical reactants and products, and how to reset and reuse the CRN multiple times will be crucial research questions.

This evaluation shows a first working stochastic chemical reaction network (SCRN) design for an SIC algorithm and indicates possible effects on the algorithm design going forward. Building on this preliminary work, we will look into extending the design to more than 2 TXs, exploiting the repeatable structure of the current network, as well as more thorough optimization of the reaction rate constants, and expanding the CRN design to the parameter optimization scheme shown in [6].

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