Experiments with Shadow Cancellation

This document details several experiments with shadow cancellation on a Rock-Paper-Scissors oscillator and presents the results.

Initial concentrations

The concentrations of the signal species are as follows

$$Ak = 11\ nM, Br = 10\ nM \text{ and } Cj = 3\ nM$$

The concentrations of the React, Produce complexes are set to 100 nM, and the Helper strands' concentrations are set to 75 nM.

Concentrations of the cancellation complexes is set to 20 nM.

RPS Oscillator w/o Shadow Cancellation

Figure 1 shows two RPS oscillators corresponding to the original and shadow circuits (note that the original circuit is hidden as both the oscillators embody equivalent dynamics). We notice that both the circuits leak prodigiously and dissociate within 2500 seconds.

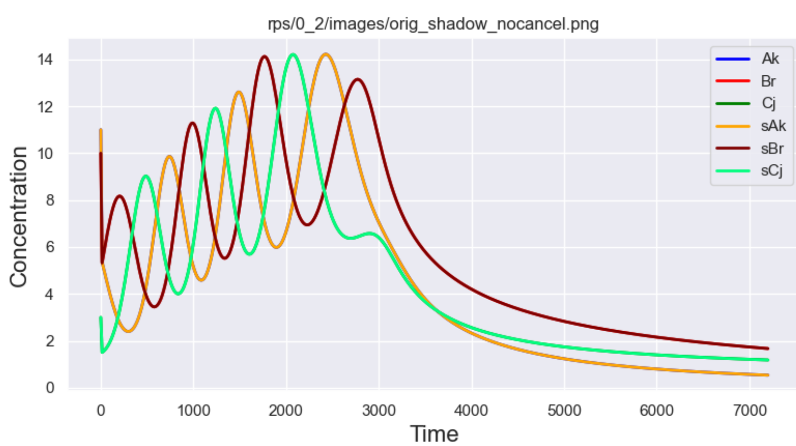


Figure 1: RPS oscillator "original" and "shadow" circuits with leaks introduced into both the circuits.

RPS Oscillator with Shadow Cancellation

We notice in Figure 2 that shadow cancellation improves the performance of the RPS oscillator by enabling the oscillations to persist until t=6000s.

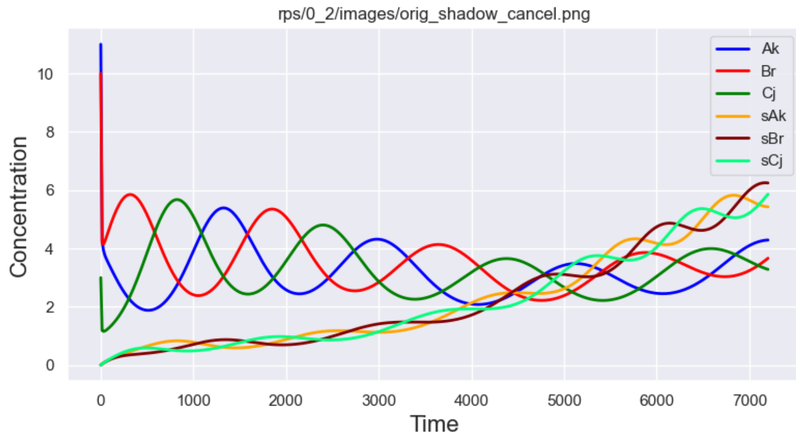


Figure 2: 2 RPS Oscillator with "original" circuit and "shadow" circuit. Notice that the oscillations are extended further.

RPS Oscillator after Perturbing the Shadow Circuit

20% Perturbed

Without cancellation

Here, the shadow circuit is perturbed by 20% i.e., all the rate constants in the shadow circuit are increased by 20%. (i.e., $k_{pert} = k(1 + 0.2)$). Notice that there is a phase difference b/w the original and shadow circuits. Species of the shadow circuit are marked with a prefix *s*.

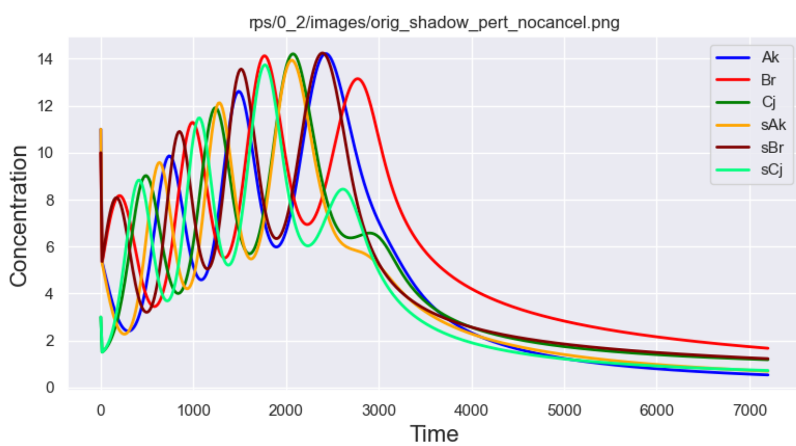


Figure 3: RPS Oscillators of original and perturbed shadow circuits. The rate constants of all the reactions of the shadow circuit are increased by 20%

With cancellation

Shadow cancellation extends the time for which the oscillations persist from t=2500s to t=6000s. Further, the dynamics match closely with the "unperturbed" setting in Figure 4.

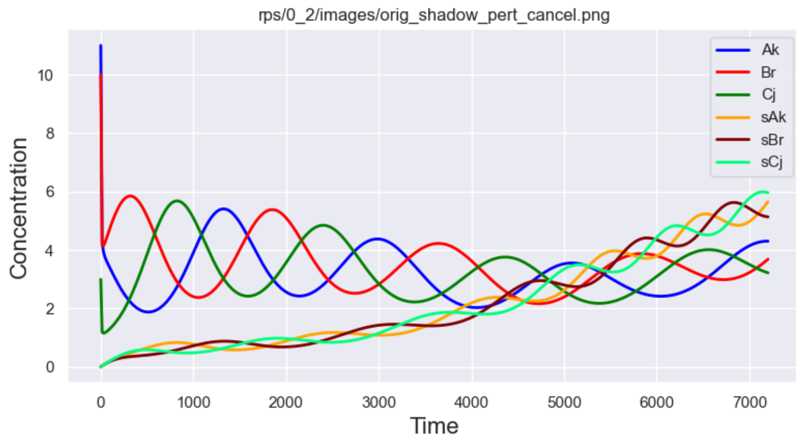


Figure 4: RPS Oscillator of original and perturbed shadow circuits with shadow cancellation using Cancel Complexes.

90% Perturbed

Without cancellation

The rate constants of the shadow circuit are perturbed by 90% of their actual value. Figure below shows the circuit dynamics. Notice that the original and shadow circuits are out of phase, even more than in Figure 3.

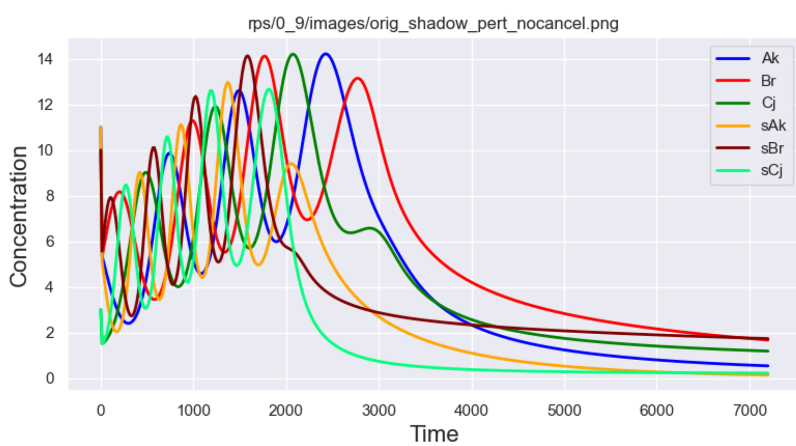


Figure 5: RPS Oscillator with the rate constants of the shadow circuit perturbed by 90%.

With cancellation

The rate constants of the shadow circuit are perturbed by 90% of their actual value and the cancellation complexes are applied. Notice that the oscillations persist till t=6000s. Further, the dynamics match closely with the "unperturbed" setting in Figure 2.

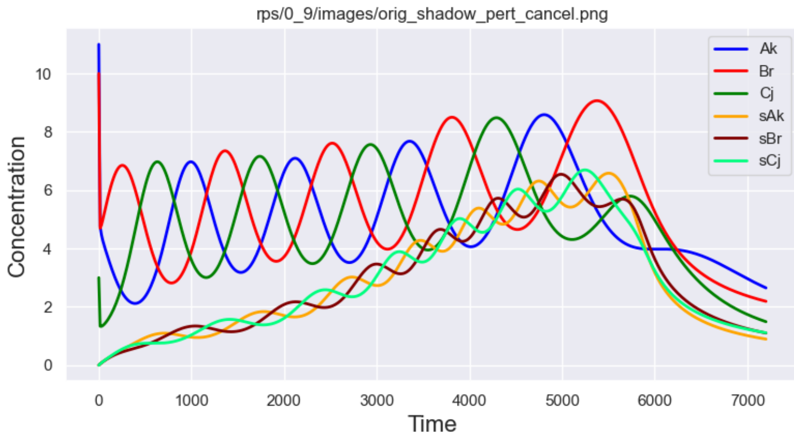


Figure 6: RPS Oscillator with the rate constants of the shadow circuit perturbed by 90% and the application of cancellation complexes.

Discussion

- Perturbation of the rate constants of the shadow circuit to test the out-of-phase synchronization of the original and shadow circuits.
- Both 20% and 90% perturbation of rate constants doesn't disturb the oscillatory behavior and yields results similar to the no perturbation case (Figure 2), which is quite peculiar.
- We have currently set the concentration of the cancellation complex to 20 nM. We notice that the signal strands in the shadow circuit have non-zero concentrations. This is owing to the fact that the cancellation complexes are present in lesser than the required concentration.
- Higher concentrations of the cancellation complexes sequester too many signal strands from the solution through a phenomenon known as toehold occlusion[1]. Therefore, the concentrations of the cancellation complexes need to be carefully set.
- **Next:** All the cancellation complexes have the same concentrations. Perhaps, they have to be adaptive.

[1] Tianqi Song, Nikhil Gopalkrishnan, Abeer Eshra, Sudhanshu Garg, Reem Mokhtar, Hieu Bui, Harish Chandran, and John Reif. Improving the performance of DNA strand displacement circuits by shadow cancellation. *ACS Nano*, 12(11):11689–11697, November 2018

Analysing the leak

In this section, we analyze the leak dynamics by tracing the concentration of a chemical species from the shadow circuit sAk, the complement strand for Ak. As explained before, we trace its path at three different perturbations–0, 0.2, and 0.9–rate constants.

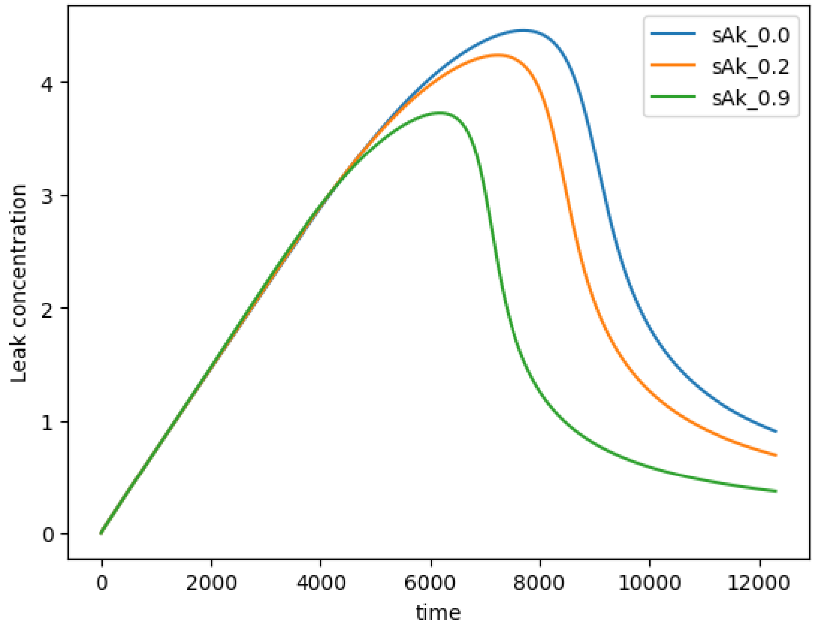


Figure 7: Concentration of the shadow strand *sAk* due to circuit leak starting from a *zero* initial concentration.

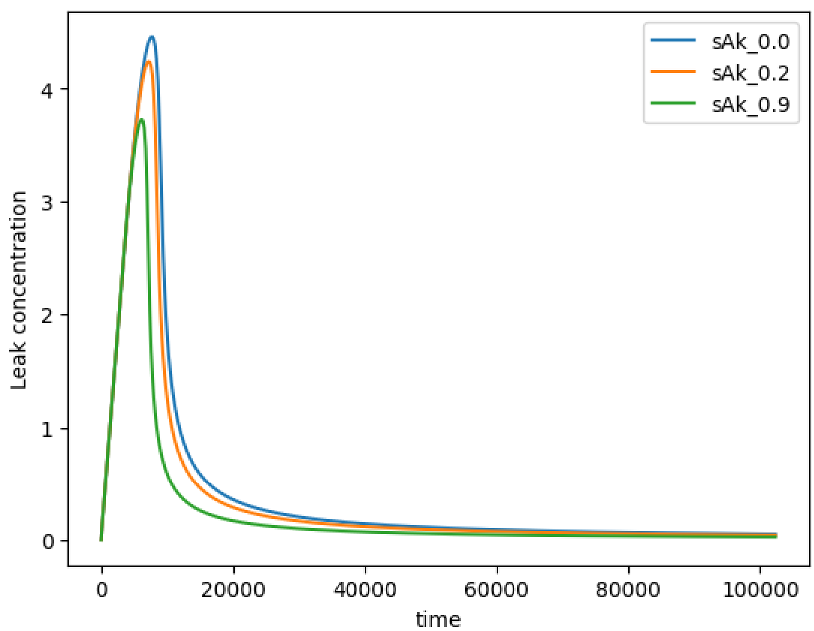
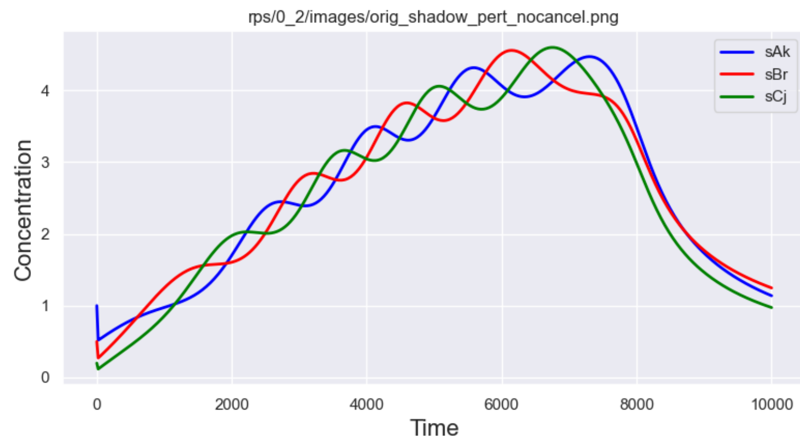


Figure 8: Concentration of the shadow strand *sAk* due to circuit leak starting from a *zero* initial concentration. This is the same as Figure 7 but runs for a longer time.

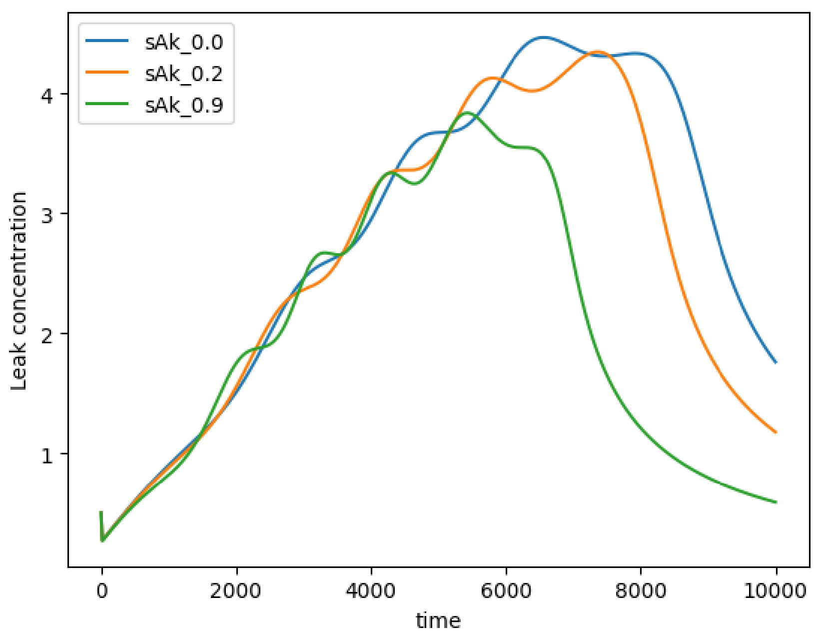
When the shadow strands have a small initial concentration

Now, we give a small initial concentration to the shadow strands, assuming that they all don't follow the same dynamics due to some extraneous factors. Here, we set, $sAk = 0.5\ nM, sBr = 0.3\ nM,$ and $sCj = 0.1\ nM$. Figure 9 shows that the shadow strands exhibit oscillations similar to the RPS oscillator around the path in Figure 7.

Figure 9: Concentrations of the shadow strands sAk, sBr, sCj when given slight initial concentrations, accounting for unforeseen extraneous factors.



(a) The dynamics of the shadow strands $sAk, sBr,$ and sCj at a perturbation of 0.2 of the rate constants.



(b) Comparision of the dynamics of the shadow strand sAk at different perturbations $0, 0.2, 0.9$

References

[SGE+18] Tianqi Song, Nikhil Gopalkrishnan, Abeer Eshra, Sudhanshu Garg, Reem Mokhtar, Hieu Bui, Harish Chandran, and John Reif. Improving the performance of DNA strand displacement circuits by shadow cancellation. *ACS Nano*, 12(11):11689–11697, November 2018.