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Influence of receptor recharge on the statistics of captured particles

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We consider a setup in which n particles are initially released into a domain and diffuse freely. Part of the boundary consists of absorbing "escape" regions, where the particles can escape the domain, and reflecting regions. The rest of boundary consists of "capture" regions (receptors), that can switch between being reflecting and absorbing. Specifically, after capturing a particle, the capture region becomes reflecting for an exponentially distributed amount of time (recharge time). We are interested in the distribution of the number of particles that are captured before they escape.

Our mathematical results are derived from considering our system in several ways: as a full spatial diffusion process with recharging traps on the boundary; as a continuous-time Markov process approximating the original system; and lastly as a system of ODEs in a mean-field approximation.

Considering the full spatial diffusion process, we prove that the total expected number of the captured particles has an upper-bound of the order of ($\log n$). We then consider a few examples investigating the implications of this result, including a neural system in which recharge reduces the number of neurotransmitter bindings by several orders of magnitude.

Seeking additional understanding of this process over a wide range of parameter values, we then present a well-defined algorithm to approximate the full spatial diffusion process with a continuous-time Markov process in order to eliminate computationally expensive simulations. We highlight the conditions required for the approximation to yield similar quantitative results as the full spatial process. We then apply the approximation, and the associated mean-field model, to investigate time courses for the expected number and higher ordered statistics of captured particles. Specifically, we find that the number of expected captures as a function of time appears to grow linearly, before leveling off, and find an analytical expression for the duration of the linear growth. This result may be particularly helpful for understanding applications where multiple puffs of particles are inserted in the domain over a period of time (e.g. neuronal synapses), and can provide a bound on the time between puff events such that particles in different puffs no longer interact. We also find that the amount of variation observed in the total number of captured particles varies non-monotonically with the mean recharge time. Lastly, we combine these results together to predict stochastic properties of intracellular signals resulting from receptor activation.

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