MEAN FIELD FOR MARKOV DECISION PROCESSES: FROM DISCRETE TO CONTINUOUS OPTIMIZATION

Nicolas Gast,
Bruno Gaujal
Jean-Yves Le Boudec,
Jan 24, 2012

INRIA

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Contents

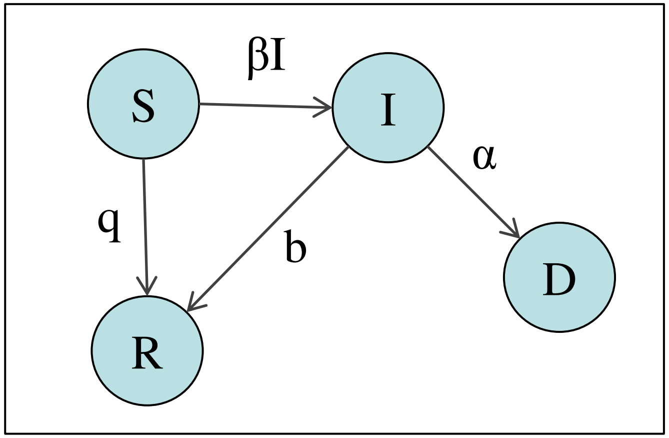
1

MEAN FIELD INTERACTION MODEL

Mean Field Interaction Model

- Time is discrete
- N objects, N large
- Object n has state $X_n(t)$
- $(X^N_1(t), \ldots, X^N_N(t))$ is Markov
- Objects are observable only through their state

- "Occupancy measure" $M^N(t)$ = distribution of object states at time t
- Example [Khouzani 2010]: M^N (t) = (S(t), I(t), R(t), D(t)) with
  S(t)+ I(t) + R(t) + D(t) =1
  S(t) = proportion of nodes in state `S'



Mean Field Interaction Model

- Time is discrete
- N objects, N large
- Object n has state $X_n(t)$
- $(X^N_1(t), \ldots, X^N_N(t))$ is Markov
- Objects are observable only through their state

- "Occupancy measure" $M^N(t)$ = distribution of object states at time t
- ***Theorem*** [Gast (2011)] $M^N(t)$ is Markov
- Called "*Mean Field Interaction Models*" in the Performance Evaluation community [McDonald(2007), Benaïm and Le Boudec(2008)]

Intensity *I(N)*

- $I(N)$ = expected number of transitions per object per time unit

- A mean field limit occurs when we re-scale time by $I(N)$
  i.e. we consider $X^N(t/I(N))$

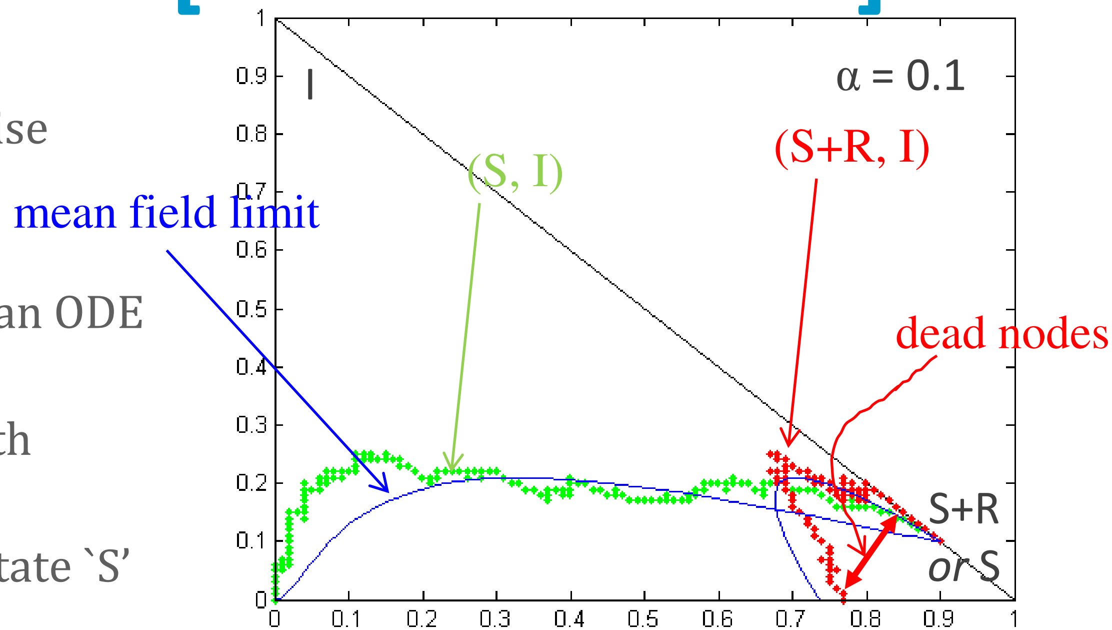
- I(N) = O(1): mean field limit is in discrete time
  [Le Boudec et al (2007)]

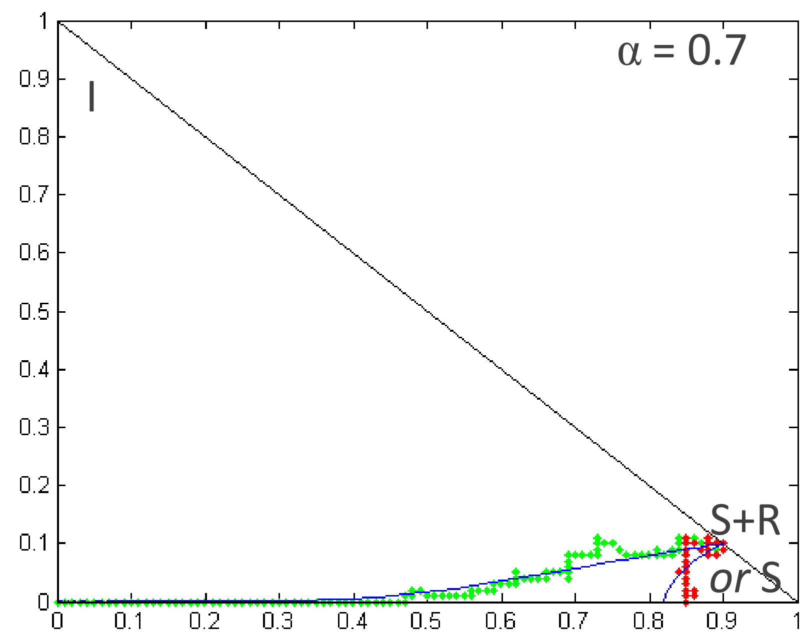
  I(N) = O(1/N): mean field limit is in continuous time
  [Benaïm and Le Boudec (2008)]

Virus Infection [Khouzani 2010]

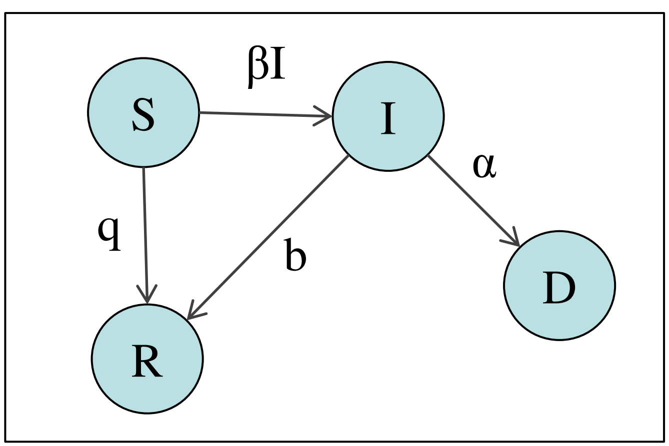
- *N* nodes, homogeneous, pairwise meetings
- One interaction per time slot, I(N) = 1/N*;* mean field limit is an ODE
- Occupancy measure is M(t) = (S(t), I(t), R(t), D(t)) with S(t)+ I(t) + R(t) + D(t) =1

  S(t) = proportion of nodes in state `S'





N = 100, q=b=0.1, β =0.6



The Mean Field Limit

- Under very general conditions (given later) the occupancy measure converges, in law, to a deterministic process, *m(t),* called the *mean field limit*

$$M^N\left(\frac{t}{I(N)}\right) \to m(t)$$

- Finite State Space => ODE

Sufficient Conditions for Convergence

- [Kurtz 1970], see also [Bordenav et al 2008], [Graham 2000]
- Sufficient conditon verifiable by inspection:

  [Benaïm and Le Boudec(2008), Ioannidis and Marbach(2009)]

  - Let $W^N(k)$ be the number of objects that do a transition in time slot k. Note that $\mathbb{E}\left(W^N(k)\right) = NI(N)$, where $I(N) \stackrel{\text{def}}{=}$ intensity. Assume

  $$\mathbb{E}\left(W^N(k)^2\right) \leq \beta(N) \quad \text{with} \quad \lim_{N\to\infty} I(N)\beta(N) = 0$$

  Example: I(N) = 1/N
  Second moment of number of objects
  affected in one timeslot = o(N)

- Similar result when mean field limit is in discrete time
  [Le Boudec et al 2007]

2

MEAN FIELD INTERACTION MODEL WITH CENTRAL CONTROL

Markov Decision Process

- Central controller
- ***Action state A*** (metric, compact)
- Running reward depends on state and action
- ***Goal***: maximize expected reward over horizon *T*
- ***Policy π*** selects action at every time slot
- Optimal policy can be assumed ***Markovian***
  $(X^N{}_1(t), \ldots, X^N{}_N(t)) \rightarrow action$
- Controller observes only object states

=> π depends on $M^N(t)$ only

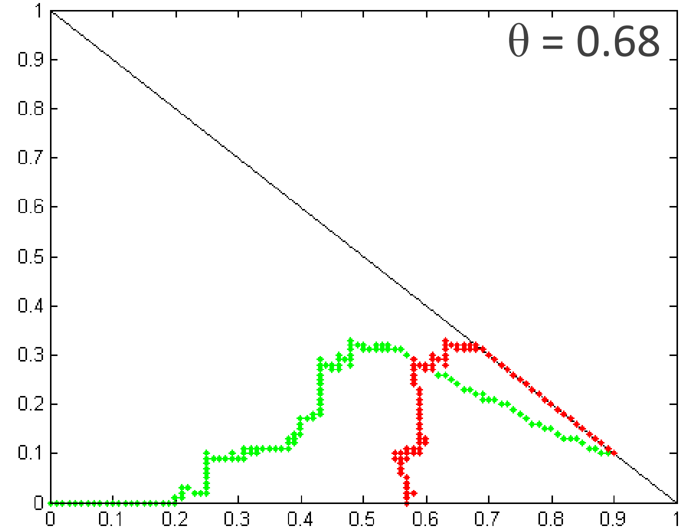
$$V_\pi^N(m) \stackrel{\text{def}}{=} \mathbb{E}\left(\sum_{k=0}^{\lfloor H^N \rfloor} r^N\left(M_\pi^N(k), \pi(M_\pi^N(k))\right) \middle| M_\pi^N(0) = m \right)$$

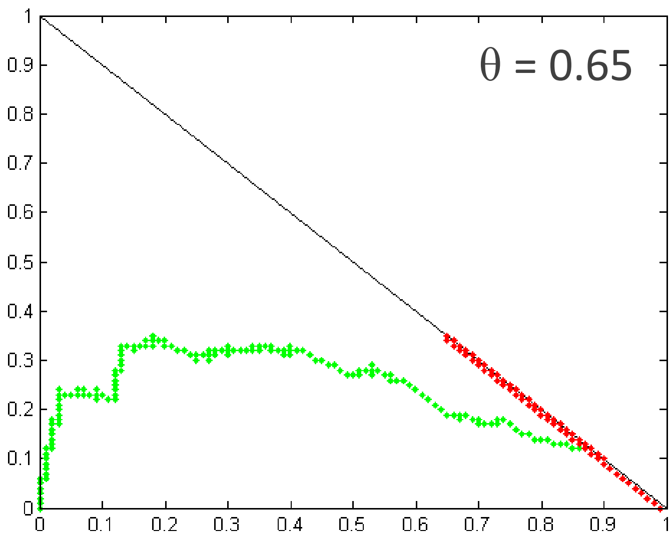
Example

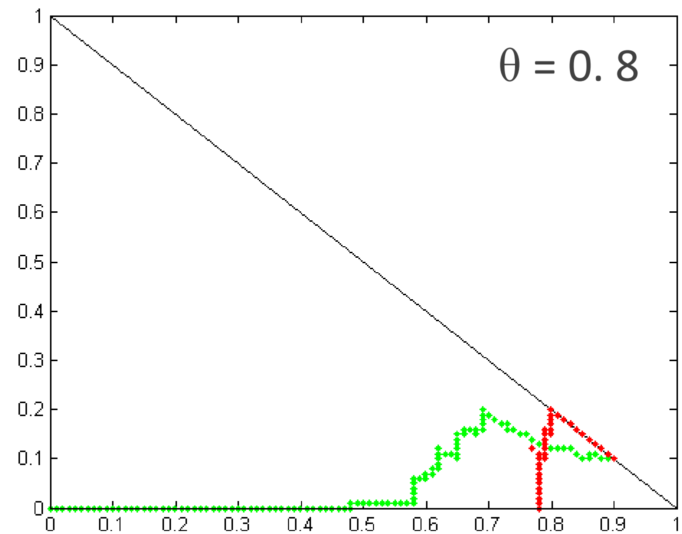
Policy π: set α=1 when R+S > θ

$$\text{Value} = \frac{1}{NT}\sum_{k=1}^{NT} D^N(k) \approx D^N(NT)$$

$$r^N(S, I, R, D, \pi) = \frac{1}{N} D$$







Optimal Control

Optimal Control Problem

- Find a policy $\boldsymbol{\pi}$ that achieves (or approaches) the supremum in

$$V_*^N(m) = \sup_{\pi} V_\pi^N(m)$$

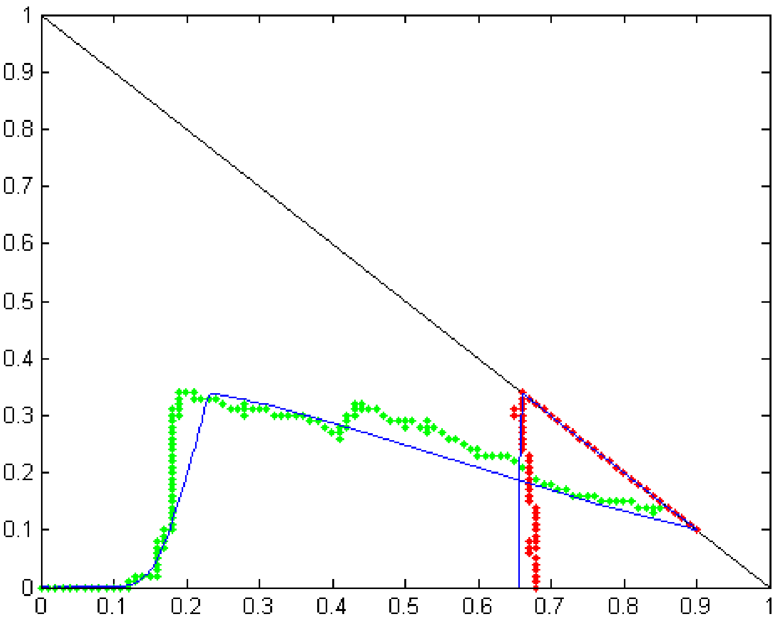
m is the initial condition of occupancy measure

- Can be found by iterative methods

- State space explosion (for *m)*

Can We Replace MDP By Mean Field Limit ?

- Assume the mean field model converges to fluid limit for every action
  - E.g. mean and std dev of transitions per time slot is O(1)



- Can we replace MDP by optimal control of mean field limit ?

Controlled ODE

- Mean field limit is an ODE
- Control = action function $\alpha(t)$
- Example:

if $t > t_0$ $\alpha(t) = 1$ **else** $\alpha(t) = 0$

$$\frac{\partial S}{\partial t} = -\beta I S - qS$$
$$\frac{\partial I}{\partial t} = \beta I S - bI - \alpha(t) I$$
$$\frac{\partial D}{\partial t} = \alpha(t) I$$
$$\frac{\partial R}{\partial t} = bI + qS.$$

- Goal is to maximize

$$v_\alpha(m_0) \stackrel{\text{def}}{=} \int_0^T r\left(\phi_s(m_0, \alpha), \alpha(s)\right) ds$$

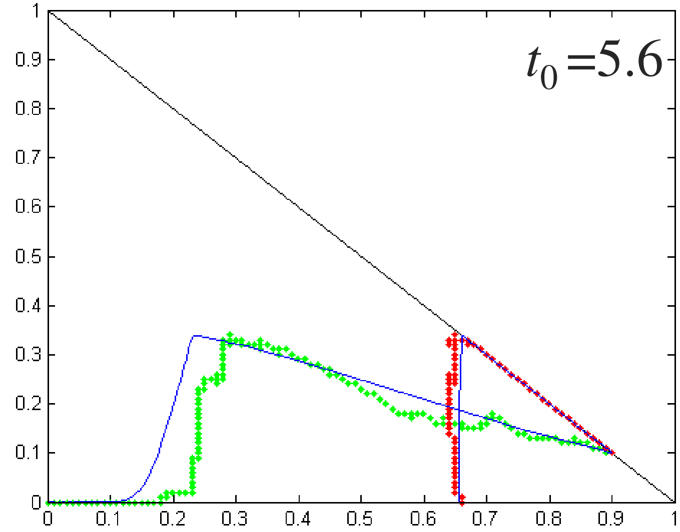
$$v_*(m_0) = \sup_\alpha v_\alpha(m_0)$$

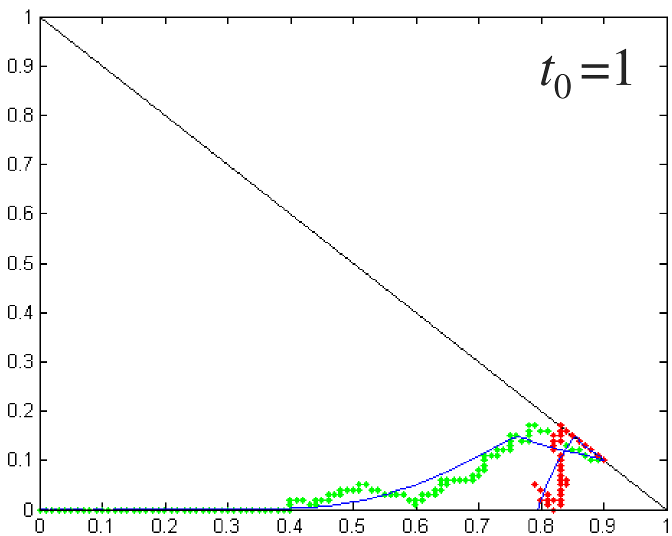
m_0 is initial condition
$r(S, I, R, D, \alpha) = D$

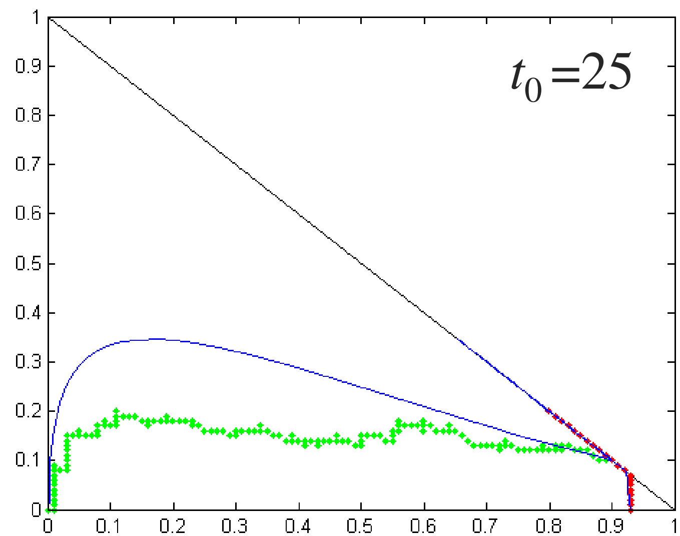
- Variants: terminal values, infinite horizon with discount

Optimal Control for Fluid Limit

- Optimal function α(t) Can be obtained with Pontryagin's maximum principle or Hamilton Jacobi Bellman equation.







3

CONVERGENCE, ASYMPTOTICALLY OPTIMAL POLICY

Convergence Theorem

- ***Theorem*** [Gast 2011]
  Under reasonable regularity and scaling assumptions:

$$\lim_{N\to\infty} V_*^N\left(M^N(0)\right) = v_*\left(m_0\right)$$

Optimal value for system with N objects (MDP)

Optimal value for fluid limit

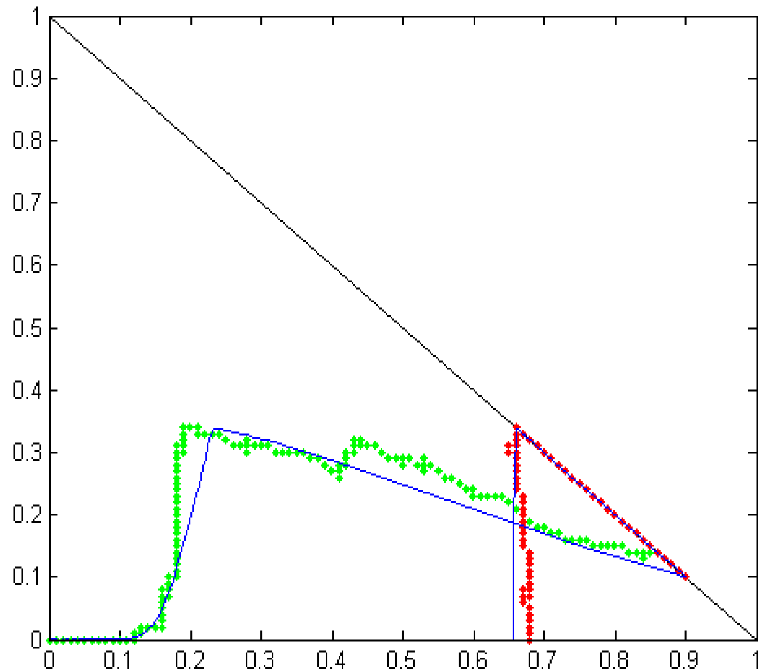
Convergence Theorem

- ***Theorem*** [Gast 2011]
  Under reasonable regularity and scaling assumptions:

$$\lim_{N\to\infty} V_*^N\left(M^N(0)\right) = v_*\left(m_0\right)$$

- Does this give us an asymptotically optimal policy ?

  Optimal policy of system with N objects may not converge



Asymptotically Optimal Policy

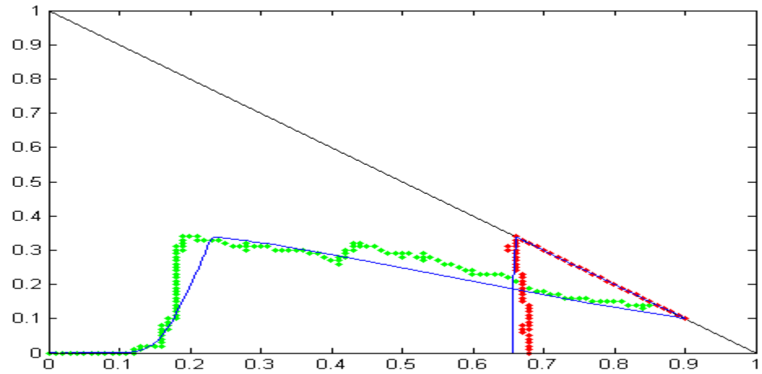
- Let α^* be an optimal policy for mean field limit
- Define the following control for the system with *N* objects
  - At time slot *k*, pick same action as optimal fluid limit would take at time *t = k I(N)*
- This defines a time dependent policy.
- Let $V_{\alpha^*}^N$ = value function when applying α^* to system with *N* objects

- ***Theorem*** [Gast 2011]

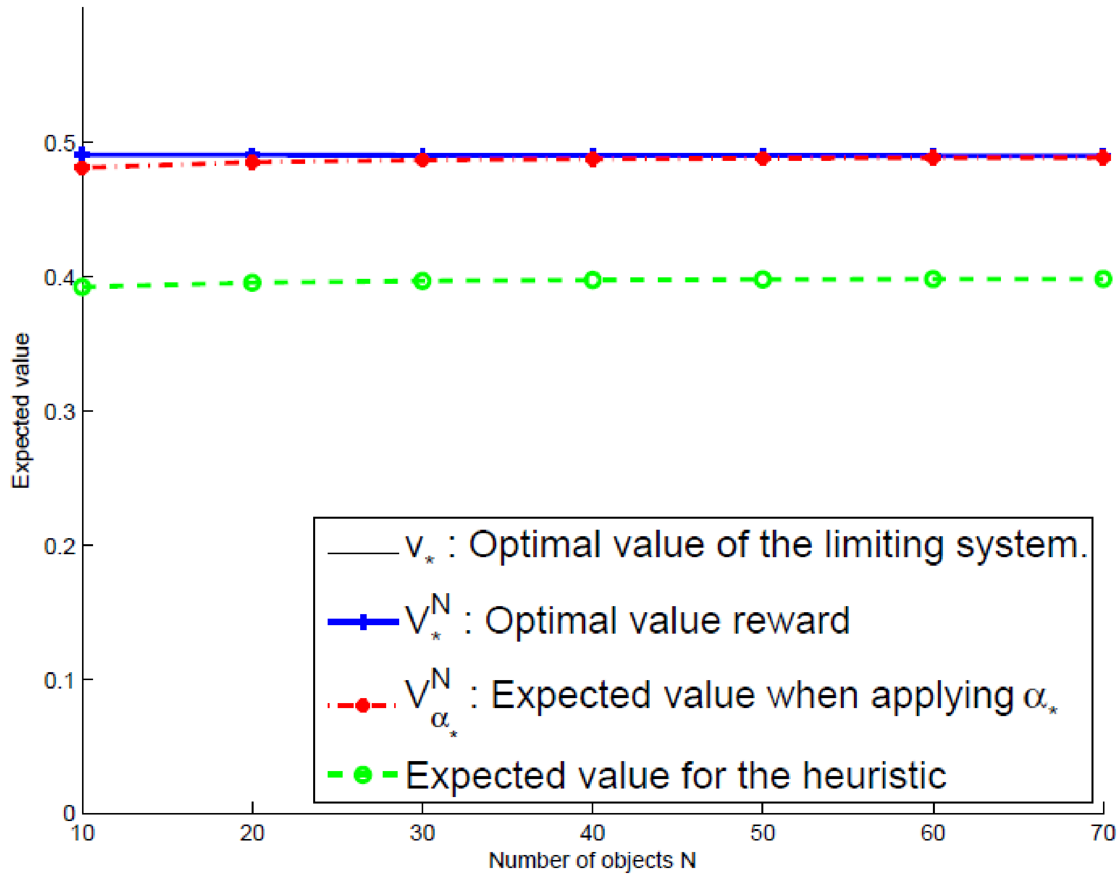
$$\lim_{N\to\infty} \left|V_{\alpha^*}^N - V_*^N\right| = 0$$

Optimal value for system with N objects (MDP)

Value of this policy



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

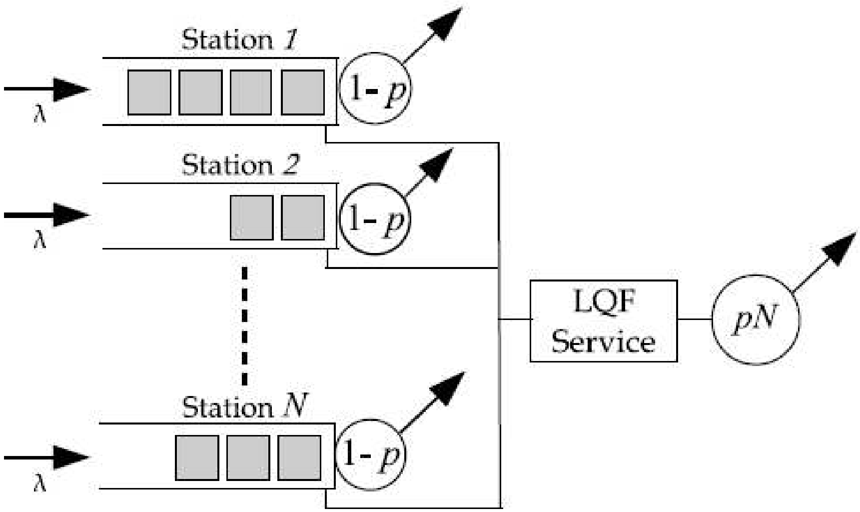


Expected value
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
Number of objects N
v_* : Optimal value of the limiting system.
V^N_* : Optimal value reward
$V^N_{\alpha_*}$: Expected value when applying α_*
Expected value for the heuristic

4

Asymptotic evaluation of policies

Control policies exhibit discontinuities



(taken from Tsitsiklis, Xu 11)

- N servers, speed 1-p
- One central server, speed pN
  - serves LQF

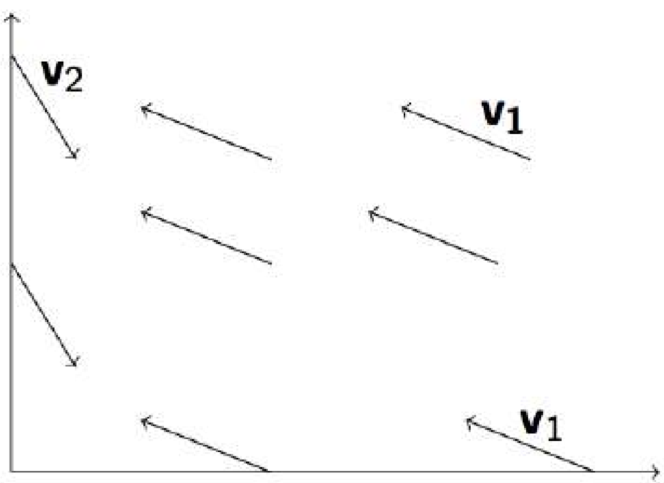
The drift is:

$$f_i(x) = \underbrace{\lambda(x_{i-1} - x_i)}_{arrivals} + \underbrace{(1-p)(x_{i+1} - x_i)}_{departures\ \ distrib} + \begin{cases} -p & \text{if } x_i > 0 \text{ and } x_j = 0 \text{ for } j > i \\ p & \text{if } x_{i+1} > 0 \text{ and } x_j = 0 \text{ for } j > i+1 \end{cases}$$

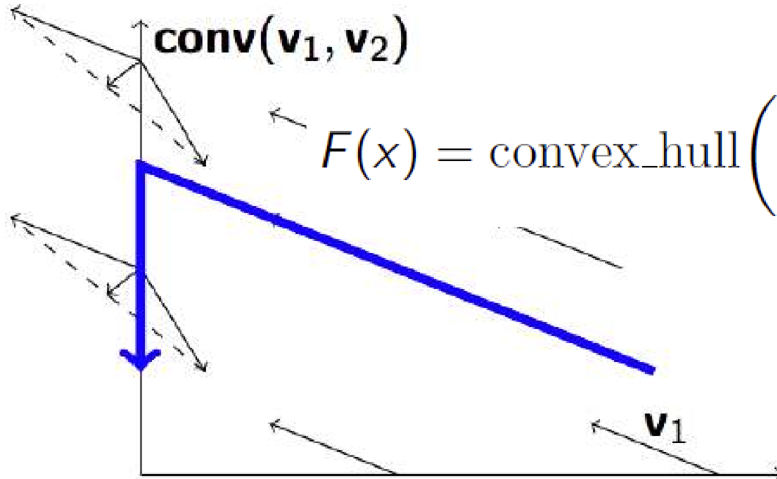
Discontinuity arrises because of the strategy LQF.

Differential inclusions as good approx.

- Discontinuous ODE:
  - Here : no solution



- Replace by differential inclusion $\dot{x} \in F(x)$

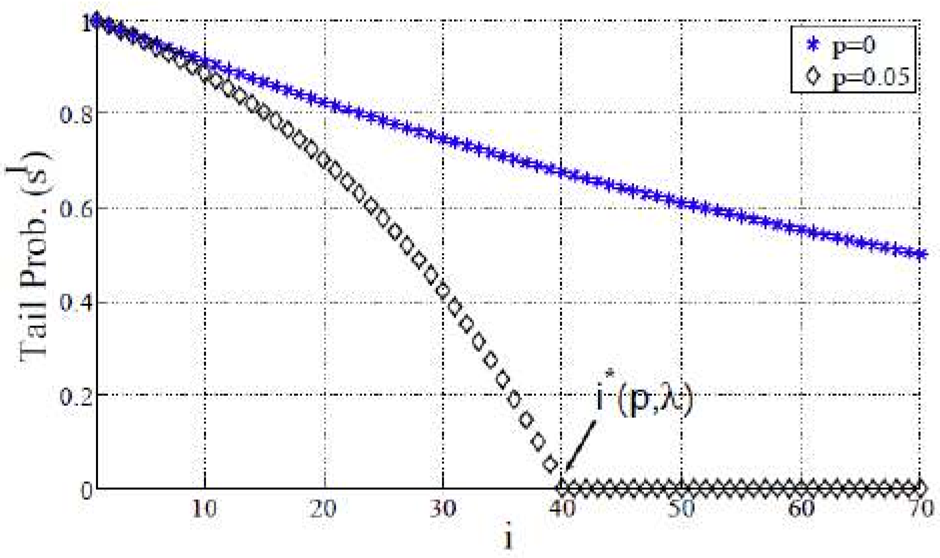


$$F(x) = \text{convex\_hull}\left(\overline{\lim_{x^N \to x}} f(x^N)\right)$$

- ***Theorem*** [Gast-2011b] Under reasonnable scaling assumptions (but without regularity)
  - The differential inclusion has at least one solution
  - As N grows, X(t) goes to the solutions of the DI.
  - If unique attractor x*, the stationary distribution concentrates on x*.

- In (Tsitsiklis,Xu 2011), they use an ad-hoc argument to show that as N grows, the steady state concentrates on

$$s_i = \begin{cases} \frac{1}{1-(p+\lambda)}\left((1-\lambda)\left(\frac{\lambda}{1-p}\right)^i - 1\right) & i \le \log_{\frac{\lambda}{1-p}} \frac{p}{1-\lambda} * \\ 0 & i > \log_{\frac{\lambda}{1-p}} \frac{p}{1-\lambda} \end{cases}$$



with $\lambda = .99$.

Easily retrieved by solving the equation $0 \in F(x)$

Conclusions

- Optimal control on mean field limit is justified
- A practical, asymptotically optimal policy can be derived
- Use of differential inclusion to evaluate policies.

Questions ?

- [Gast 2011] N. Gast, B. Gaujal, and J.Y. Le Boudec. Mean field for Markov Decision Processes: from Discrete to Continuous Optimization. To appear in *IEEE Transaction on Automatic Control*, 2012

- [Gast 2011b] N. Gast and B. Gaujal. Markov chains with discontinuous drifts have differential inclusions limits. application to stochastic stability and mean field approximation. Inria EE 7315.
  - Short version: N. Gast and B. Gaujal. Mean eld limit of non-smooth systems and differential inclusions. *MAMA Workshop*, 2010.

- [Ethier and Kurtz (2005)] Stewart Ethieru and Thomas Kurtz. Markov Processes, Characterization and Convergence. Wiley 2005.

- [Benaim and Le Boudec(2008)] M Benaim and JY Le Boudec. A class of mean field interaction models for computer and communication systems, *Performance Evaluation,* 65 (11-12): 823—838. 2008

- [Khouzani 2010] M.H.R. Khouzani, S. Sarkar, and E. Altman. Maximum damage malware attack in mobile wireless networks. *In IEEE Infocom*, San Diego, 2010