DEPARTMENT OF INFORMATION ENGINEERING

UNIVERSITY OF PADOVA

On the design of incentive mechanisms in wireless networks: a game theoretic approach

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Ciclo: XXV

Indirizzo: ICT

Supervisore: Michele Zorzi

Outline

- New design challenges
- Applications
  - Channel access
  - Flow control
- Conclusions

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Mobile communications trend

- Mobile communications grow exponentially
- Future wireless networks must manage dynamically and efficiently a large set of devices
- Networks are migrating towards more ***distributed approaches***, shifting intelligence from the core network towards the edges of the network

Global Mobile Data Traffic Growth	
2009	140%
2010	159%
2011	133%
2012 (estimate)	110%
2013 (estimate)	90%
2014 (estimate)	78%

A new design methodology

Terminals are more autonomous, more powerful, and more programmable

Issue: what if they are programmed to accomplish a personal objective?

→ a new design approach:

Distributed schemes for strategic users: the designer must provide the incentive for the users to take efficient decisions

Game theoretic approaches

Game theory is the branch of mathematics studying interactions between decision-makers

Common assumption: users are selfish and strategic, they act to maximize their own utility

Nash Equilibrium (NE)

- Existence?
- Computation?
- Uniqueness?
- Efficiency?

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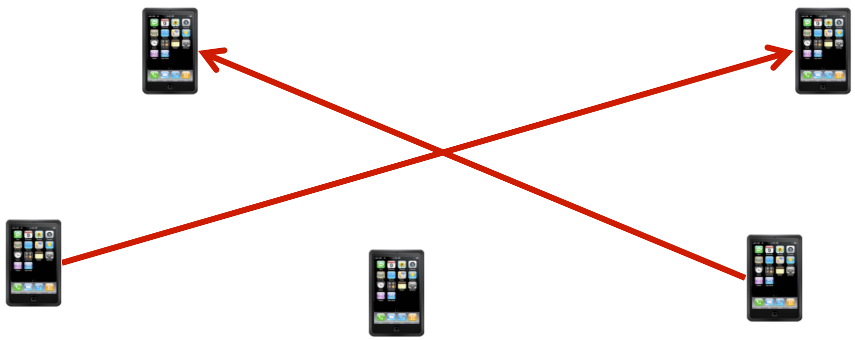
Slotted-Aloha MAC protocol



- Time is slotted and slots are synchronized
- The users contend for the channel
- A packet is received if does not collide
- i selects the transmission probability p_i
- i's throughput: $T_i(p) = p_i \prod_{j \neq i} (1 - p_j)$

Users adopt the always transmit strategy
→ network collapse

Pricing scheme

Users pay for their resource usage

Assumptions:

- i's utility: $U_i(p) = \theta_i \ln T_i(p) - c_i p_i$
- Design objective: max sum-utility

Design problem: compute the optimal unit price c_i

Results:

- Given c_i , the unique NE is $p_i^{NE} = \frac{\theta_i}{c_i}$
- Optimal pricing policy is $c_i = \sum_k \theta_k$

Intervention scheme

An intervention device is placed in the system, it can affect users' resource usage

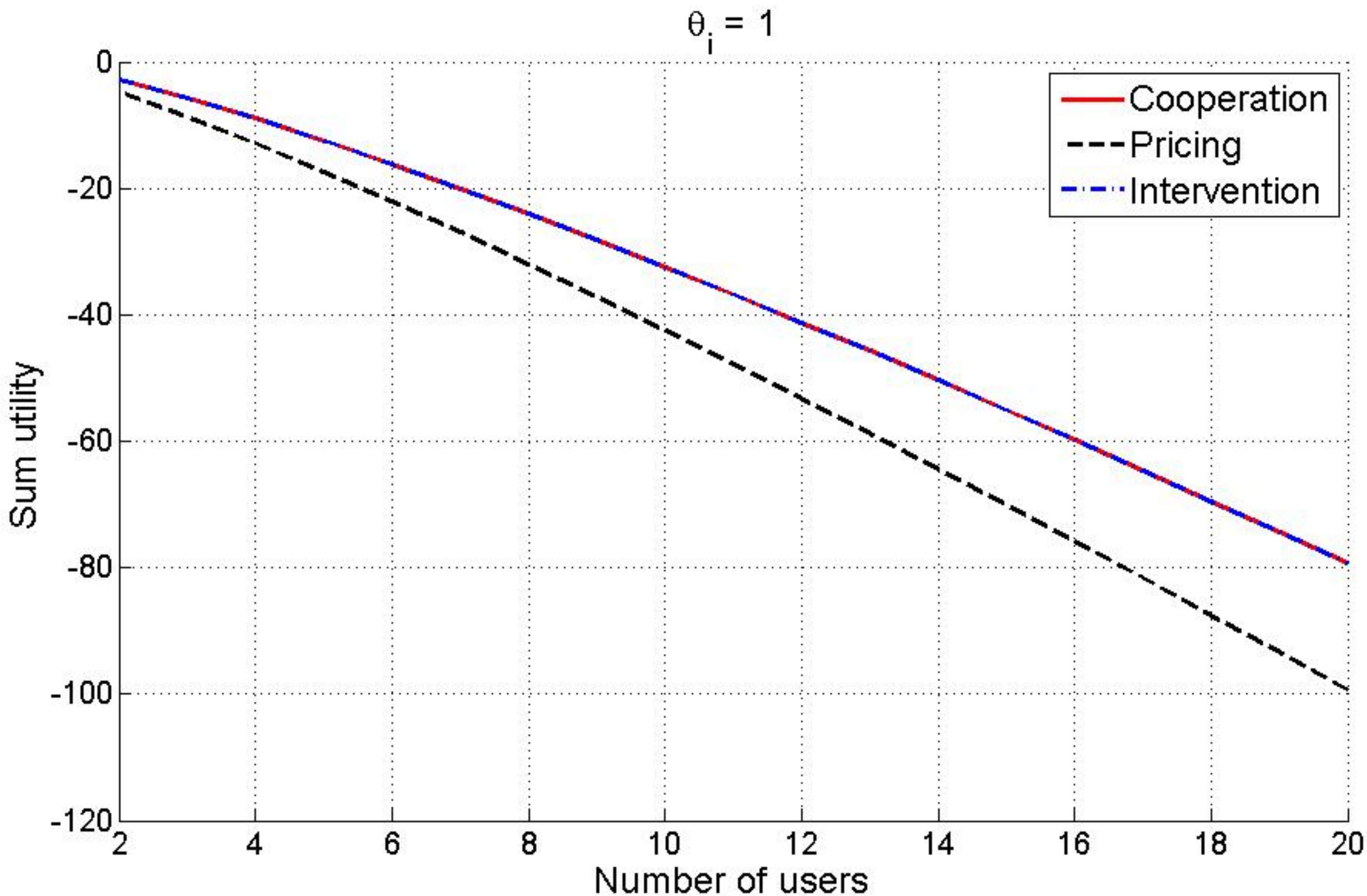
Intervention rule: a function of the users' actions
→ users' utilities can be shaped

Design problem: compute the optimal rule

Results:

- For the affine intervention rule class, the NE and the optimal rule are analytically computed

Sum utility


θi = 1
Cooperation
Pricing
Intervention
Sum utility
Number of users
0
-20
-40
-60
-80
-100
-120
2
4
6
8
10
12
14
16
18
20

Imperfect monitoring case

The proposed schemes charge / intervene based on the actions adopted by the users

Problem: what if the users' actions are not perfectly observable?

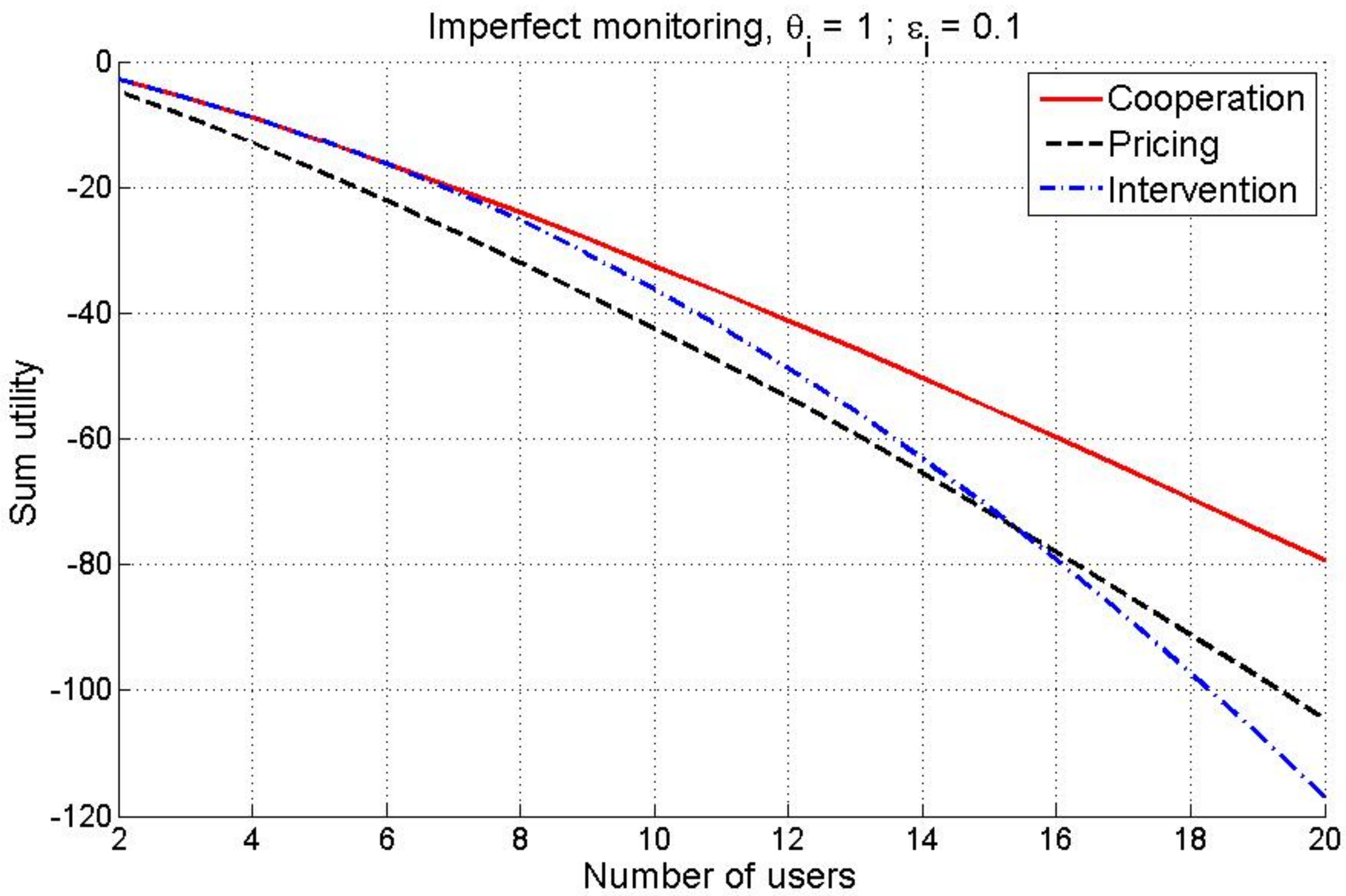
Imperfect monitoring model: $\hat{p}_i = [p_i + n_i]_0^1$

where: $n_i \sim \mathcal{U}\left[-\epsilon_i,\, \epsilon_i\right]$

Results:

- The NE and the best policies (pricing & intervention) are analytically computed

Sum utility, imperfect monitoring



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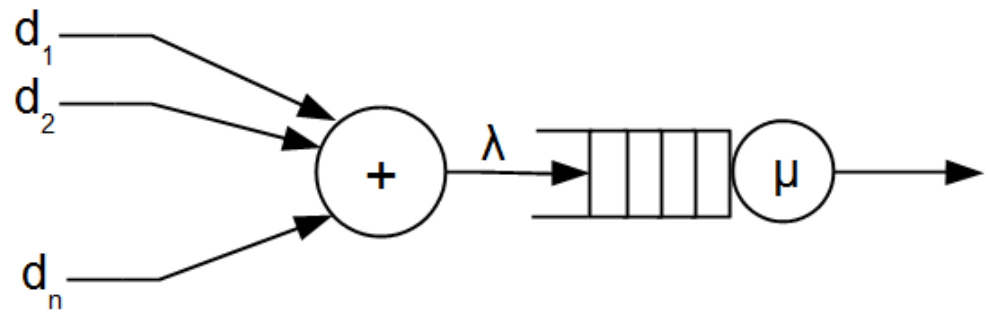
Flow control

- n users
- d_i rate user i
- service rate μ
- M/M/1 queue
- arrival rate $\lambda = \sum_{i=1}^{n} d_i$



Utility user i:

$$U_i(d, t_i) = \frac{\text{throughput}^{t_i}}{\text{average delay}} = d_i^{t_i}(\mu - \lambda)$$

Utility designer:

$$U_0(d, t) = \sqrt[n]{\prod_{i=1}^{n} U_i^{+}(d, t_i)}$$

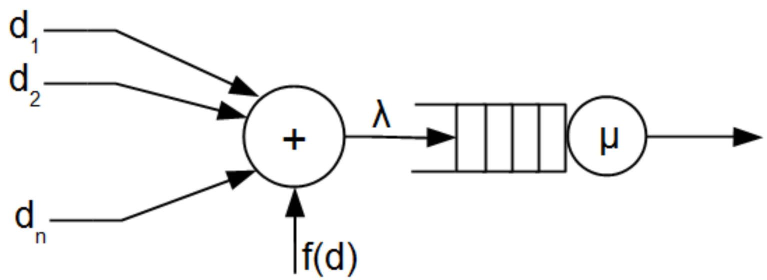
⇨

Optimal policy:

$$d_i^*(t) = \frac{t_i \mu}{n + \sum_{k=1}^{n} t_k}$$

Complete information scenario

The intervention device sends an additional flow of packets with rate given by the intervention rule f(d)

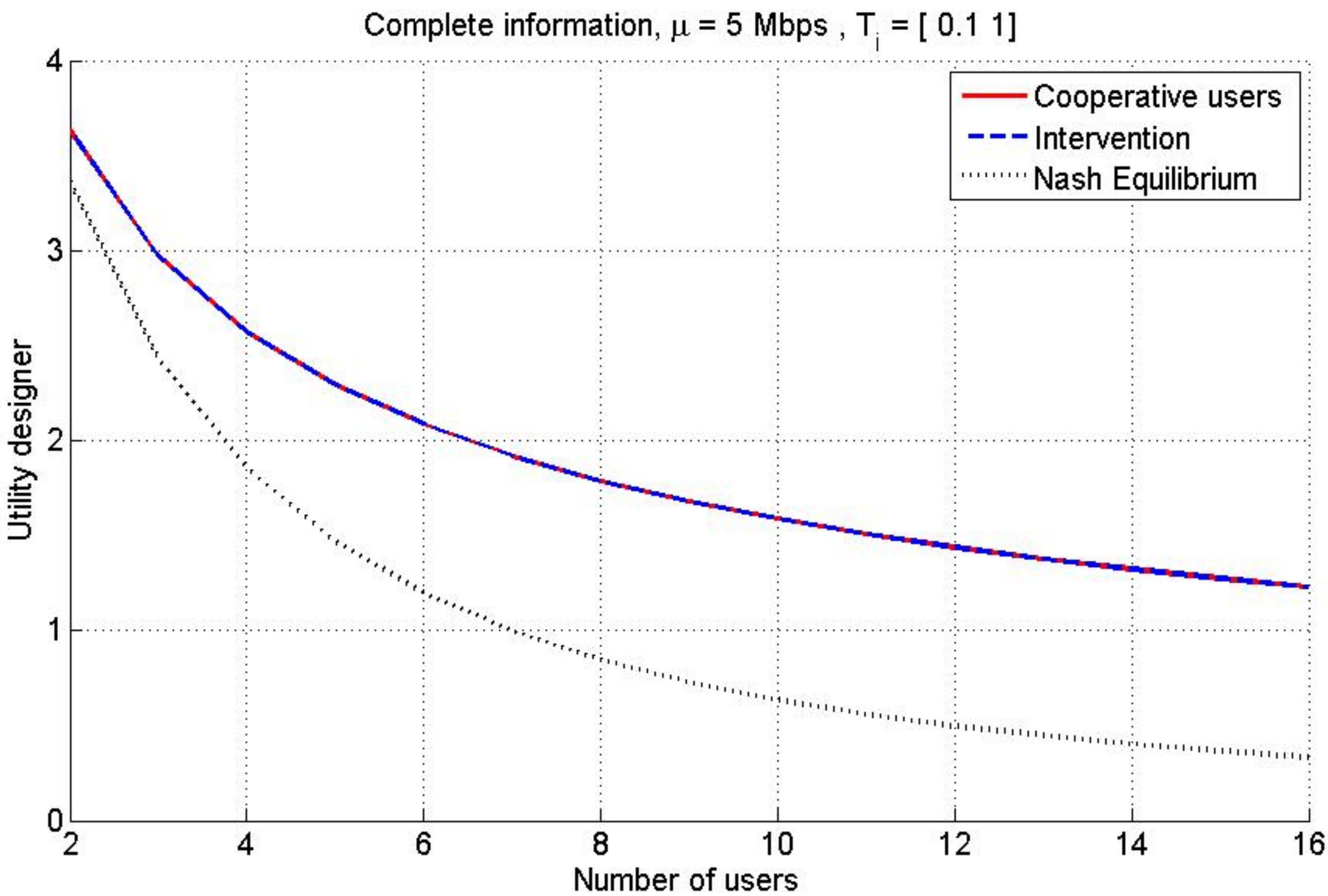


Design problem: compute the optimal rule f(d)

Results:

- For the affine intervention rule class, the NE and the optimal rule are analytically computed

Complete information results



Incomplete information scenario

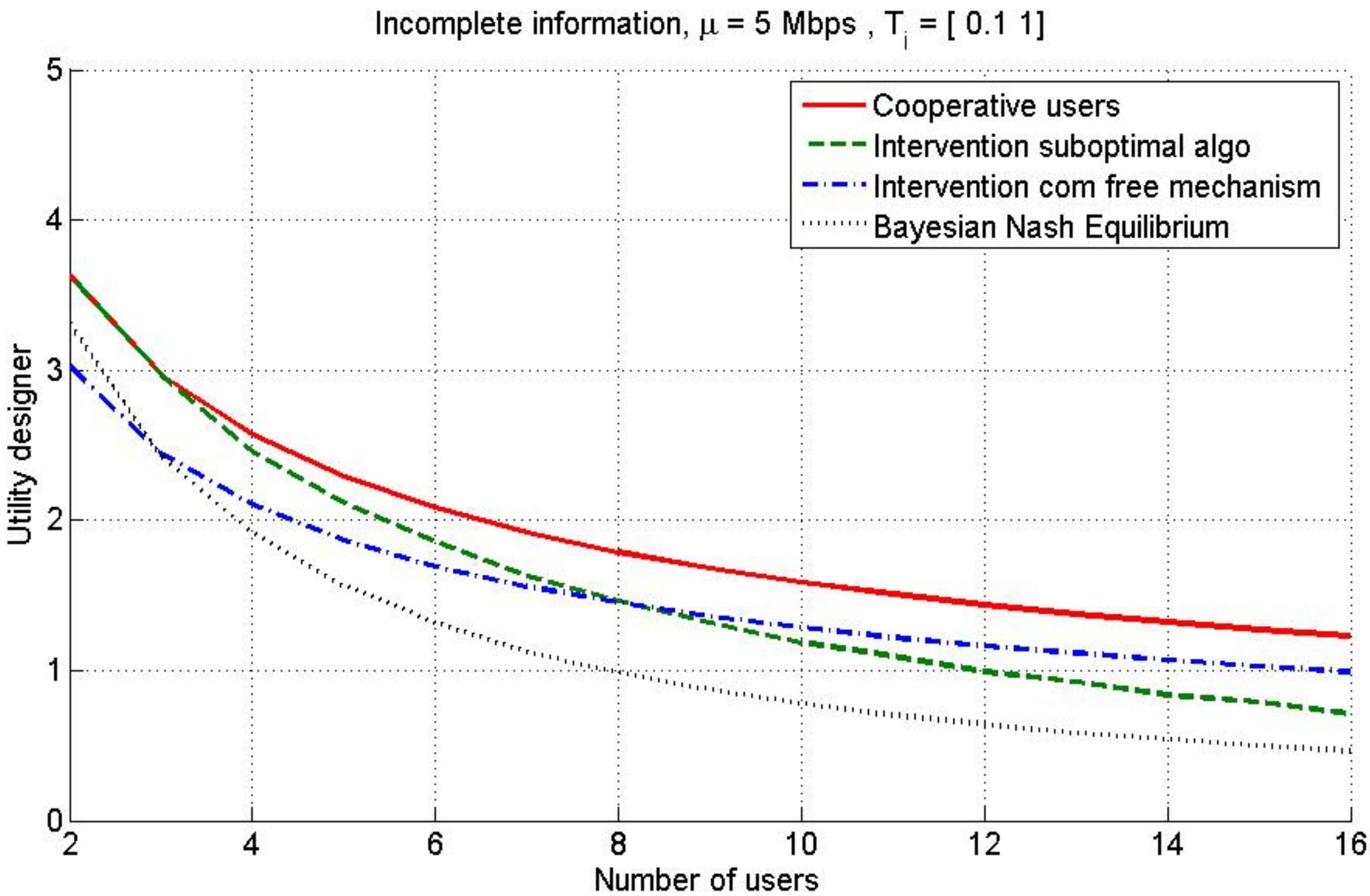
In the initialization phase the device asks the users to report their types…will they be honest?

Yes, if the scheme is ***incentive compatible (IC)*** *!!!*

Results:

- We characterized the maximum efficiency IC scheme
- We derived sufficient condition for its existence
- We proposed two suboptimal IC schemes
  - Convergent algorithm
  - Communication free mechanism

Incomplete information results



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Conclusions

- Networks require more distributed approaches, in which terminals are more autonomous and smart
- New design challenges: provide the incentive for the users to comply
- Applications to relay network, channel access, flow control
- Sometimes we can reach optimal performance (e.g., channel access perfect monitoring, flow control complete information), sometimes we can not
- But an accurate design is always able to prevent higher inefficiencies

Conference papers

1. L. Anchora, L. Badia, L. Canzian, and M. Zorzi, “A Characterization of Resource Allocation in LTE Systems Aimed at Game Theoretical Approaches”, in *Proc. IEEE CAMAD 2010*

2. L. Canzian, A. Zanella, and M. Zorzi, "Overlapped NACKs: Improving Multicast Performance in Multi-access Wireless Networks”, in *Proc. IEEE PerGroup 2010*

3. O. Pozzobon, L. Canzian, A. Dalla Chiara, and M. Danieletto, “Anti-spoofing and open GNSS signal authentication with signal authentication sequences”, in *Proc. NAVITEC 2010*

4. L. Canzian, L. Badia, and M. Zorzi, “Relaying in Wireless Networks Modeled through Cooperative Game Theory”, in *Proc. IEEE CAMAD 2011*

5. G. Quer, F. Librino, L. Canzian, L. Badia, and M. Zorzi, “Using Game Theory and Bayesian Networks to Optimize Cooperation in Ad-Hoc Wireless Networks”, in *Proc. IEEE ICC 2012*

Journal papers

1. L. Canzian, L. Badia, and M. Zorzi, “Promoting Cooperation in Wireless Relay Networks through Stackelberg Dynamic Scheduling”, *IEEE Trans. Commun.,* vol. 61, no. 2, 2013

2. L. Canzian, Y. Xiao, W. Zame, M. Zorzi, and M. van der Schaar, “Intervention with Private Information, Imperfect Monitoring and Costly Communication”, *to appear in IEEE Trans. Commun.*

3. L. Canzian, Y. Xiao, W. Zame, M. Zorzi, and M. van der Schaar, “**Intervention with Complete and Incomplete Information: Application to Flow Control**”, *to appear in IEEE Trans. Commun.*

4. G. Quer, F. Librino, L. Canzian, L. Badia, and M. Zorzi, “Inter-Network Cooperation exploiting Game Theory and Bayesian Networks”, *to appear in IEEE Trans. Commun.*

5. L. Canzian, Y. Xiao, M. Zorzi, and M. van der Schaar, “**Game Theoretic Design of MAC Protocols: Pricing and Intervention in Slotted-Aloha**”, *submitted to IEEE/ACM Trans. Networking*

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Channel access

Mathematical details: intervention perfect monitoring

The intervention device jams i's packets with probability given by the intervention rule

$$f_i^I(p_i) = [r_i(p_i - \tilde{p}_i)]_0^1$$

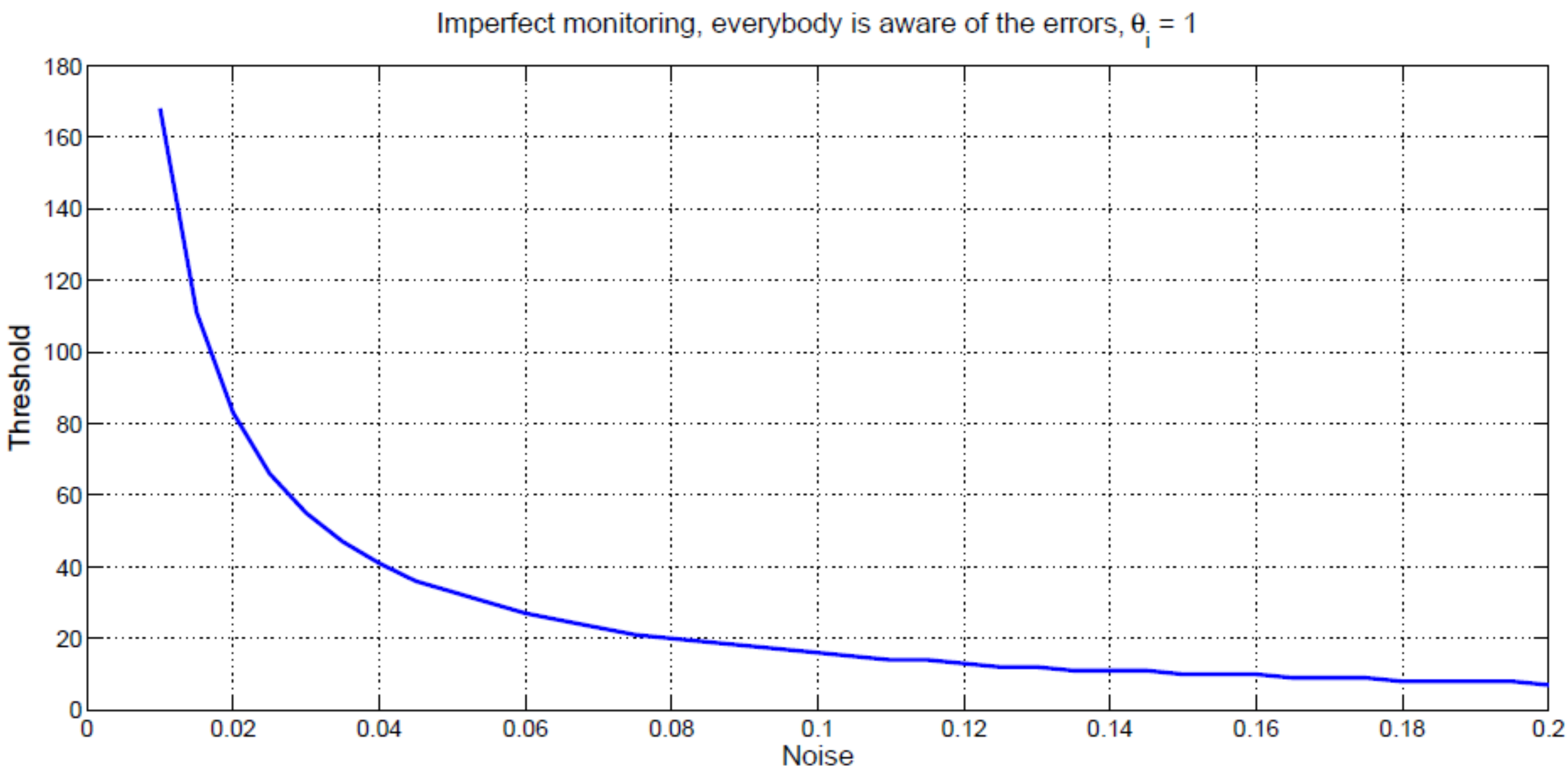
Design problem: compute the optimal rule r_i , $\tilde{p}_i$

If $r_i \geq \dfrac{1}{\tilde{p}_i}$, the best NE is: $p_i = \tilde{p}_i$

Optimal rule: $r_i \geq \dfrac{1}{\tilde{p}_i}$, $\tilde{p}_i = \dfrac{\theta_i}{\sum_k \theta_k}$

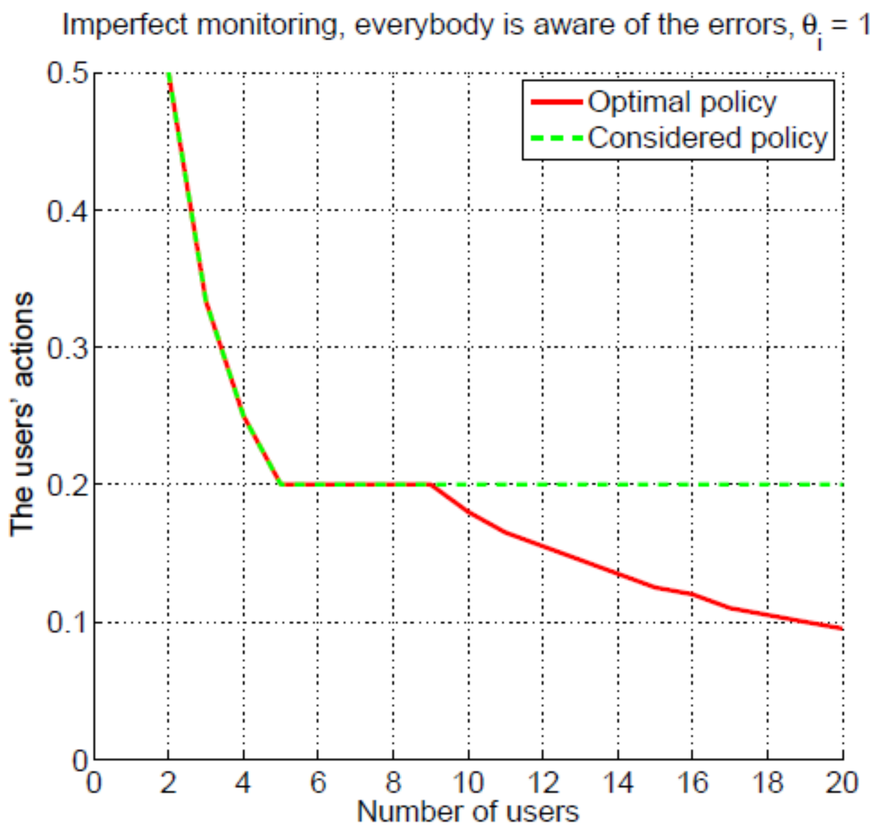
Channel access

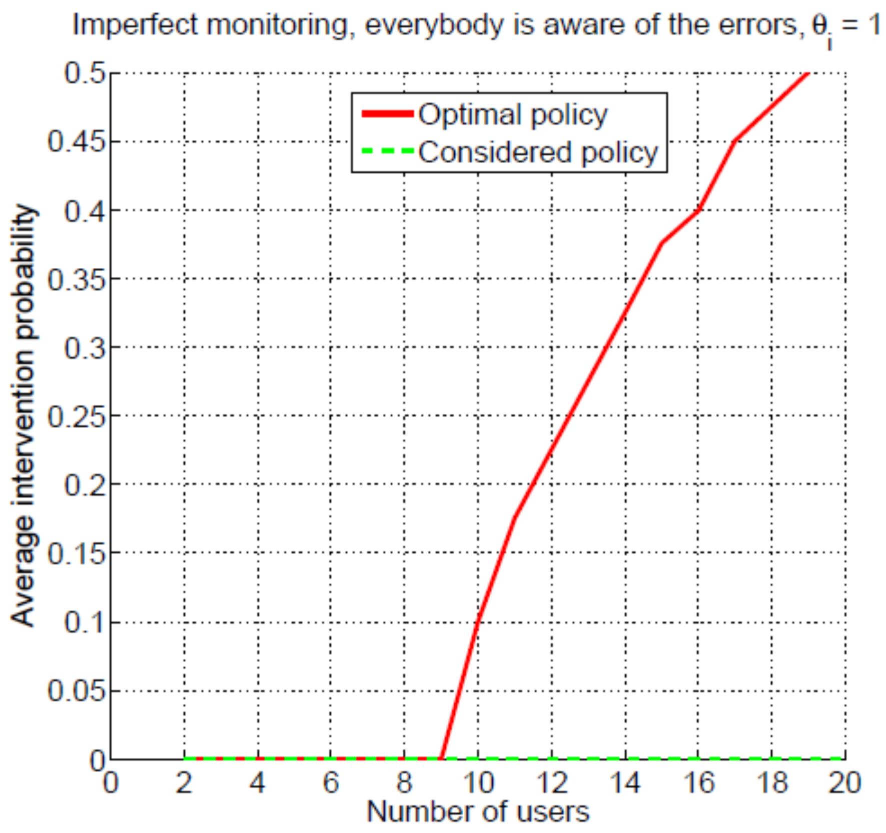
Threshold vs. - imperfect monitoring scenario



Channel access

The action of the users and the device – imperfect monitoring





Flow control

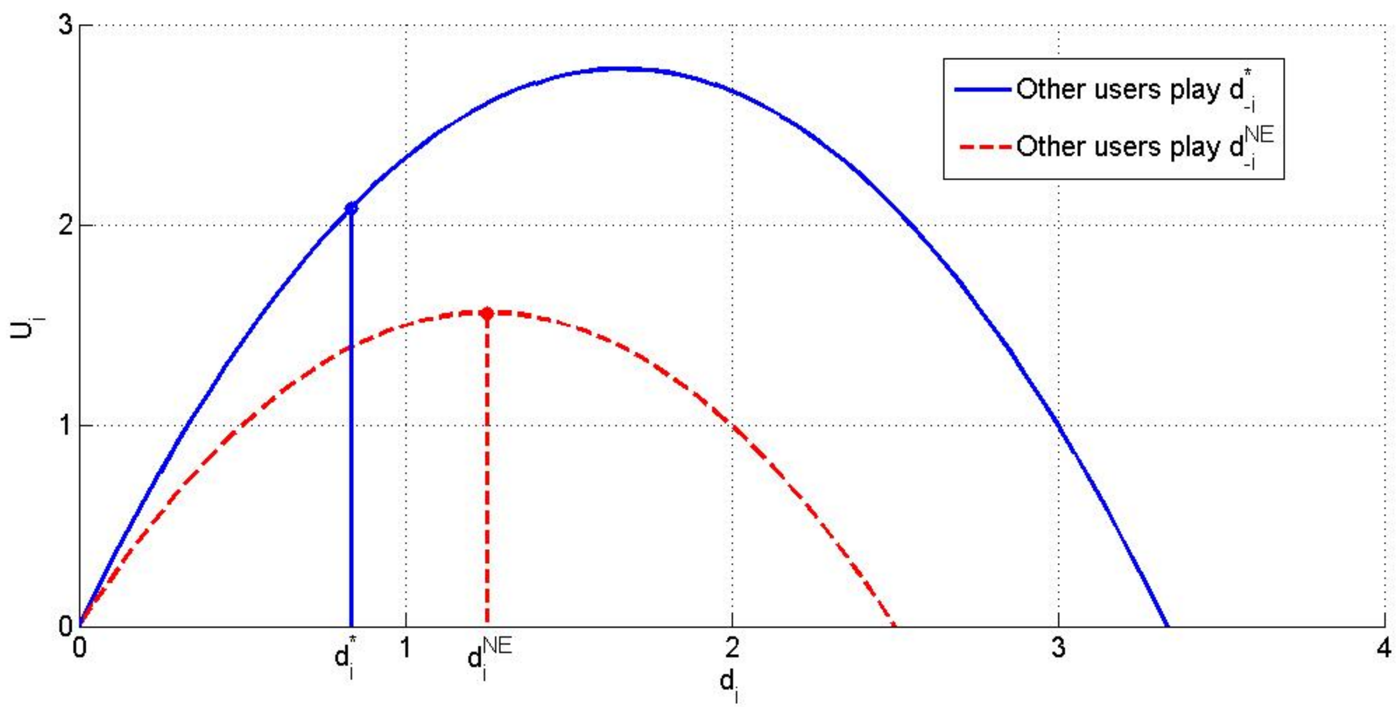
Optimal action profile vs. NE action profile complete info scenario

Optimal action profile

$$d_i^*(t) = \frac{t_i \mu}{n + \sum_{k=1}^{n} t_k}$$

NE action profile

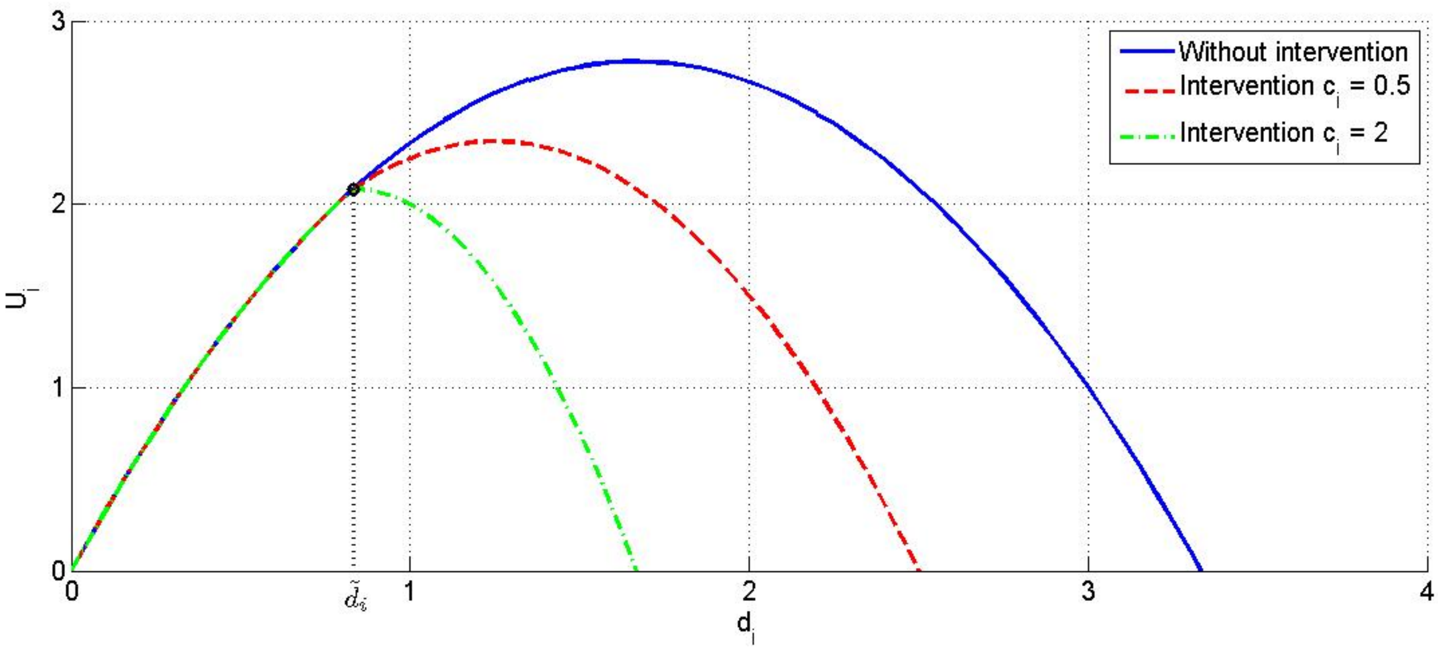
$$d_i^{NE^0}(t) = \frac{t_i \mu}{1 + \sum_{k=1}^{n} t_k}$$



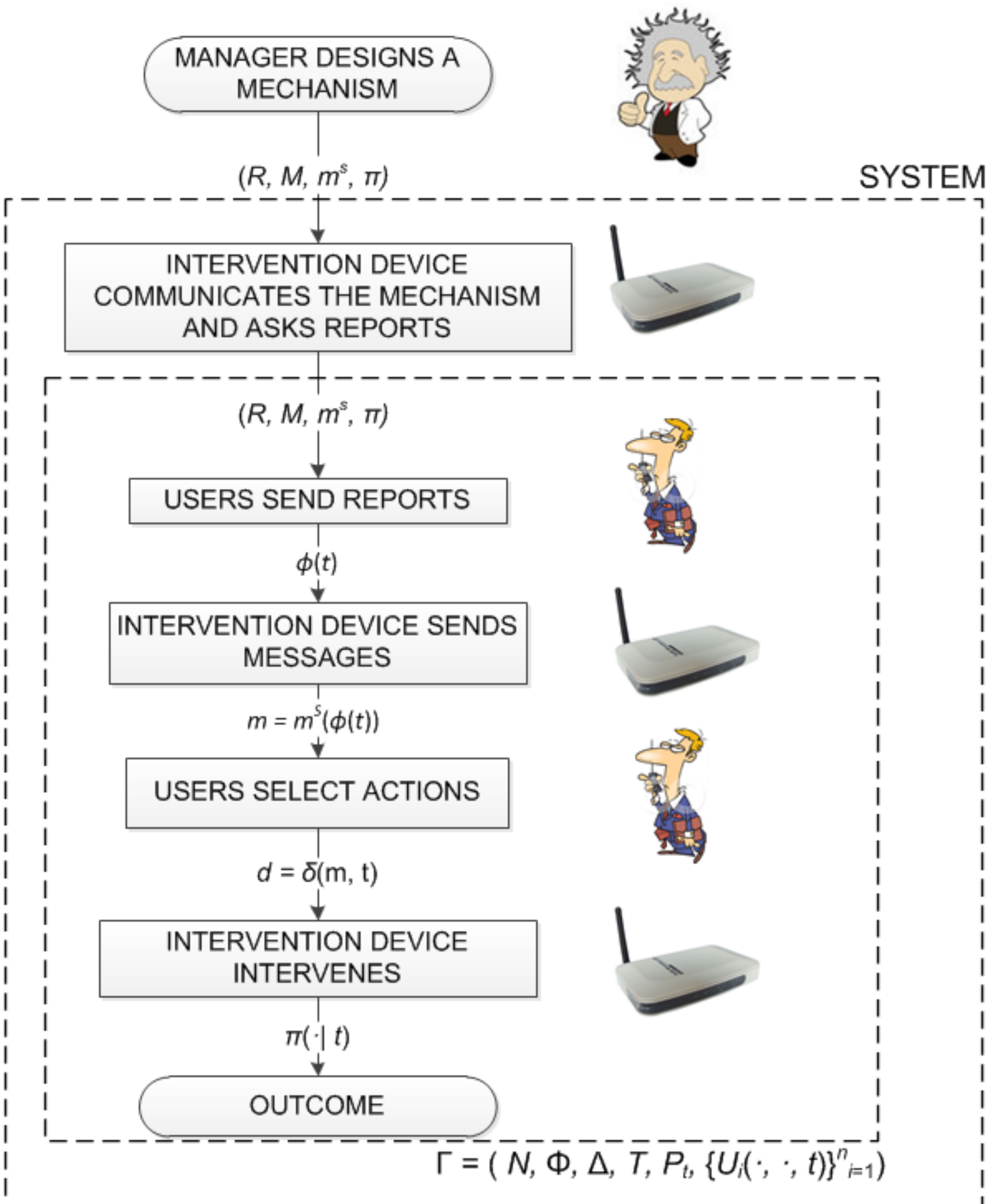
Flow control

The effect of the affine intervention rule complete info scenario

$$f(d) = \left[\sum_{i=1}^{n} c_i(d_i - \tilde{d}_i)\right]_0^{d_0^M}$$



Flow control



Given the mechanism

$$(R, M, m^S, \pi)$$

User interaction modeled through the game

$$\Gamma = \left(\mathcal{N}, \Phi, \Delta, T, P_t, \{\overline{U}_i(\cdot,\cdot,t)\}_{i=1}^{n}\right)$$

Report strategy

$$\phi_i : T_i \rightarrow R_i$$

Action strategy

$$\delta_i : M_i \times T_i \rightarrow D_i$$

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Flow control

Maximum efficiency mechanism

Lemma (T, M, d^S, π) *is a maximum efficiency incentive compatible direct mechanism*

$$\Longleftrightarrow$$

1: *the optimal action profile* $d^*(t)$ *of the game* Γ_t *is sustainable without intervention in* Γ_t

2: *the suggested action profile is the optimal action profile of game* Γ_t, *i.e.,* $d^S(t) = d^*(t)$;

3: *the intervention rules selected with positive probability sustain without intervention* $d^*(t)$

4: *users have incentives to report their real types when they adopt the suggested action profile, i.e,*

$$\sum_{t_{-i} \in T_{-i}} P_t(t \mid \tau_i) U_i \left(d_0^*, d^S(t), t\right) \geq \sum_{t_{-i} \in T_{-i}} P_t(t \mid \tau_i) U_i \left(d_0 *, d_{-i}^S(\hat{\tau}_i, t_{-i}), \hat{\delta}_i(d_i^S(t_{-i}, \hat{\tau}_i)), t\right)$$

$$\forall i \in \{1, ..., n\}, \ \forall \tau_i \in T_i, \ \forall \hat{\tau}_i \in T_i,$$

1 is valid, **2** and **3** say how to select the mechanism, **4** is valid if, $\forall \tau_k \in T_i$ and $\forall t_{-i} \in T_{-i}$

$$\left(\frac{n + \sum_{j \neq i} t_j + \tau_{k+1}}{n + \sum_{j \neq i} t_j + \tau_k}\right)^{\tau_k + 1} \left(\frac{\tau_k}{\tau_{k+1}}\right)^{\tau_k} \geq 1$$

Flow control

Decoupled problem

Proposition

$$\overline{d}^S = \operatorname*{argmax}_{d^S} \sum_{t \in T} P_t(t) U_0\left(d_0^*, d^S(t), t\right)$$

subject to:

$$\sum_{t_{-i} \in T_{-i}} P_t(t \mid \tau_i) U_i\left(d_0^*, d^S(t_{-i}, \tau_i), t\right) \geq$$

$$\geq \sum_{t_{-i} \in T_{-i}} P_t(t \mid \tau_i) U_i\left(d_0^*, d_{-i}^S(t_{-i}, \hat{\tau}_i), \hat{\delta}_i(d_i^S(t_{-i}, \hat{\tau}_i)), t\right)$$

$$\forall i \in \{1, ..., n\}, \ \ \forall \tau_i \in T_i, \ \ \forall \hat{\tau}_i \in T_i, \ \ \forall \hat{\delta}_i : D_i \to D_i$$

and $\forall t \in T$,

$$\overline{\pi}(f \mid t) = \begin{cases} 1 & \textit{for a certain } f \in \mathcal{F}^{\overline{d}^S, t} \\ 0 & \textit{otherwise} \end{cases}$$

describe an optimal mechanism, and the affine intervention rules is optimal with respect to Γ

Flow control

Proposed algorithm

Algorithm 2 Flow control suboptimal algorithm.

1: **Initialization**: $\forall\, t \in T$, $d^S(t) = d^*(t)$, $\pi(\tilde{f} \mid t) = 1$ for a certain $\tilde{f} \in \mathcal{F}^{d^S,t}$ and $\pi(f \mid t) = 0$ for $f \neq \tilde{f}$.

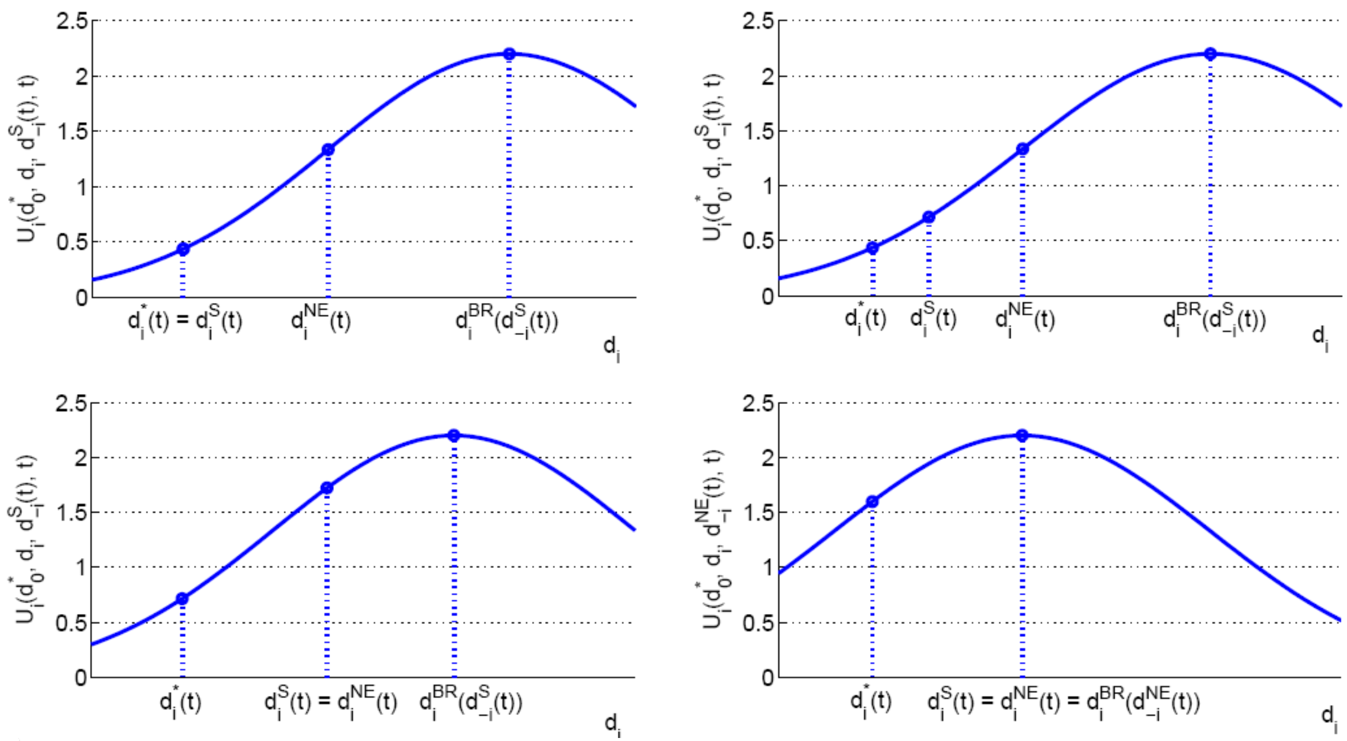
2: **For** $s = 1 : m$

3: **For** $l = 1 : m$

4: **If** $W_i(\tau_s, \tau_s) < W_i(\tau_s, \tau_l)$

5: $d_i^S(\tau_l, t_{-i}) \leftarrow \min\left\{d_i^S(\tau_l, t_{-i}) + \epsilon_i,\ d_i^{NE^0}(\tau_l, t_{-i})\right\}$, $\pi(\tilde{f} \mid t) \leftarrow 1$ for a certain $\tilde{f} \in \mathcal{F}^{d^S,t}$ and $\pi(f \mid t) = 0$ for $f \neq \tilde{f}$, $\forall\, t_{-i} \in T_{-i}$

6: Repeat from 2 until 3 is unsatisfied $\forall\, s$ and l



Flow control

Proposed a priori mechanism

A priori mechanism: independent on users reports

Proposed a priori mechanism:
Suggested action profile $\overline{d}$ and intervention rule

$$f(d) = \left[\sum_{i=1}^{n} c_i (d_i - \overline{d}_i)\right]_0^{d_0^M} \quad , \quad c_i > \frac{\tau_m \left(\mu - \sum_{k=1}^{n} \overline{d}_k\right) - \overline{d}_i}{\overline{d}_i} \quad , \quad d_0^M \geq \mu$$

Where $\overline{d}$ is the solution of the convex problem:

$$\underset{d}{\operatorname{argmin}} - \ln\left(\mu - \sum_{i=1}^{n} d_i\right) \mathbb{E}_t \left[\prod_{i=1}^{n} d_i^{\frac{t_i}{n}}\right]$$

$$d_i \geq 0 \quad , \quad d_i \leq \mu \quad , \quad \forall i \in \mathcal{N}$$

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Flow control

Manager's expected utility vs. low type probability incomplete information scenario