Technical-economic management of communication networks: prices, games, auctions and mechanisms for medium-access and power control

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Outline

Why decentralised control?

- Complexity of central controllers
- Lack of local information at central controller
- Signalling overhead
- Some application scenarios are **inherently** decentralised
  - peer-to-peer computing
  - infrastructureless (adhoc) networks

The free market as a distributed algorithm

- A free market operates in a largely decentralised manner:
  - An authority sets up some general “rules of interaction”
  - Many “small” agents make relatively simple decisions, based on simple rules and local knowledge
- A “base line” for efficiency: an allocation is “Pareto efficient” if NO reallocation can make someone better-off without making somebody else worse off
- First welfare theorem: under certain idealisations, a “free market” yields a Pareto efficient allocation
- A complex technological system can be “efficiently” managed as an “economy”
- Microeconomics and game/auction/mechanism-design theory provide a solid analytical foundation

A technological system as an "economy"

- The system can be viewed as integrated by many "agents"
- Agents may correspond to actual human beings, or may be machines, or processes
- The system administrator sets up some relatively simple rules for resource use and behaviour (prices, auctions, rewards, punishments, etc)
- Each agent behaves and utilises resources as an economic entity seeking to maximise its "preferences" while obeying the rules and budget constraints (energy, power, bandwidth, etc).
- If the rules are "right", the complex system produces "efficient" results

Power Control in Cellular Networks

- Why is power control important?
  - CDMA, the technology of 3G networks, is interference limited
  - Power employed by a terminal becomes interference to another
  - Power control increases the capacity of a CDMA system by limiting interference
  - It also extends battery life
- Power control among data terminals has been fruitfully formulated as a "game"[1]

What is a Game?

- A game: each of several players chooses a "strategy" in order to receive a "payoff"
- Payoff to a player depends on the choices by ALL players
- Each player is "selfish"
- Key solution concept: Nash equilibrium
  An allocation (a strategy per player) such that no player would gain by unilaterally "deviating" (changing strategy) (⇐a **Nobel** idea from "a beautiful mind"[2])
- Nash equilibria are generally (Pareto) "inefficient"

Power Control Game

- Players: CDMA data transmitting terminals
- Strategy: transmission power level
- Payoff : number of bits successfully transmitted per unit energy (bits/Joule)
- Signal-to-interference ratio determines bits/Joule
- A Nash equilibrium generally exists
- Equilibrium power levels are “too high”
- Challenge: how to get selfish terminals to choose lower power levels “on their own”

Toward efficient decentralisation

- To induce lower power levels : “tax” power
  - Original: Terminal chooses power p to maximise its “utility” $u(p; I)$ given interference, I
  - New: Terminal maximises $u(p; I) - cp$ with c chosen by network administrator
- Problems
  - Resulting allocation is “better” but still inefficient
  - There are technical difficulties

Mechanism design for efficiency

note: **2007 Economics Nobel Prise** given to those who laid the foundation of Mechanism Design!

- "mechanism" : a set of procedures, penalties and rewards designed to guide selfish entities toward a desired outcome
- Example: Vickery's Second Price Auction ⇐another **Nobel** idea!
  - Each player submits a "sealed" bid for an object
  - Highest bidder gets object
  - But winner pays highest losing bid
  - Each player's best response is to bid its true valuation of object: "truth-telling" is optimal

A Compensation mechanism

- Proposed by Varian in a general context[3]
- Applies whenever a choice by an entity adversely affects another entity (“externality”)
- Requires a “transferable good”, say money, with which agents compensate each other
- Agents must be “well-informed”; but “naive” agents can reach the desired equilibrium by successive adjustments.
- Agents “fairly” compensate each other at equilibrium

Mechanism–Basic Idea

With only 2 terminals, suppose terminal 1 interferes with terminal 2 but *not* vice-versa. (SIC decoding)

- Terminal 2 declares the amount money (or transferable good) it wishes to charge terminal 1 as compensation for each unit of interference.
- Terminal 1 (interferer) declares the price it *offers* to pay terminal 2 as compensation.
- The interferer (#1) must pay penalty if its offered price is different from terminal 2's price

What is the ‘right thing’ to do?

- Because of the interference, terminal 2 suffers a “dis-utility”; i.e., it transmits fewer bits per Joule
- This dis-utility has a value to terminal 2 (in terms of the transferable good)
- This value is the “fair” compensation to terminal 2
- This is exactly what terminal 2 gets at equilibrium

Why does the mechanism work?

- To avoid the penalty, generally the interferer will offer to pay the exact amount terminal 2 wants
- But why doesn't terminal 2 ask "too much"?
- If price paid to terminal 2 exceeds its "true cost", then it "makes a profit" per unit of interference
- But then, it would want more interference!
- To get the interferer to produce more, terminal 2 must lower its price. At equilibrium, terminal 2 price equals its true cost

Another scenario for Varian's mechanism: UWB

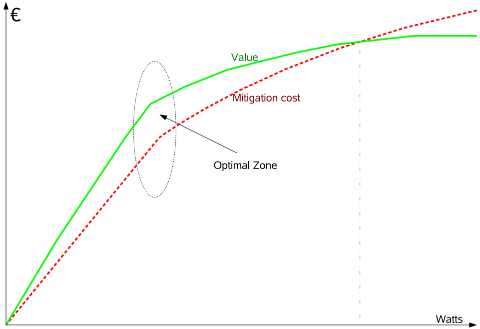
- UWB is an exciting new technology with many benefits[4]
- It can coexist over spectrum assigned to other technologies, allowing spectrum "recycling"
- Incumbent technology may be negatively affected
- Traditional approach to protecting incumbent:
  - to outlaw UWB, or (recently, and *only* in some regions)
  - to limit power emissions to level of "unintended emitters"
- Problem: Many "needs" cannot be met (range too short)
- Alternative approach: Economic mitigation
  - Basic idea: estimate the economic cost to incumbent of UWB disruption, and compensate the incumbent fairly
  - Analytical basis: work by renown economists such as Varian[3] and **Nobel-laureate** Coase[5]

Essential results on UWB coexistence

- Effect of a “large number” of UWB devices can be idealised as a uniform increase in noise
- In [6], we give in closed form the revenue loss of a 3G cell due to a “noise rise”
- “UWB” should be allowed higher power usage over 3G bands, if it covers such revenue losses
- Other possibilities exist. UWB can give incumbents:
  - more base stations (smaller cells!)
  - more “processing” (MIMO, multiuser detectors, etc)
  - even, more spectrum! (think market-driven dynamic spectrum allocation!)

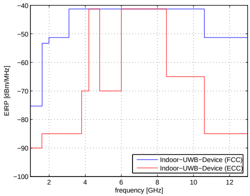
Economically-efficient emission level

- The higher the transmission power, the greater the cost of mitigation.
- There is an economically-efficient level of interference



"Invisible hand" regulation

- Other incumbent technologies can be similarly considered.
- The efficient level will depend on the spectrum band
- Thus, the regulatory "spectrum mask" can be entirely drawn by the "invisible hand" of the market



Next generation UWB

- A new generation of powerful UWB devices that can satisfy a greater set of consumer needs can arise.
- The beneficiaries contribute toward the "economic mitigation" of negative effects caused by the extra power on incumbent networks
- Present devices may continue to be allowed (exempt from economic contribution)
- Manufactures and consumers could choose whether to support one or both classes of devices

MORE POWER to the PEOPLE!!

Auctions: Why?

- Auctions have long been used (in 193 A.D. the entire Roman Empire was auctioned by the Praetorian guard. . . but the winner was beheaded 2 months later!)
- Reasons for choosing auctions include:
  - speed of sale or allocation
  - discovery of the true “value” of the offered object
  - transaction “transparency” (fraud prevention)[7]
- Applications in telecommunications include
  - Bandwidth allocation
  - spread-spectrum sharing
  - (Dynamic) spectrum allocation to networks
  - Centralised MAC (cellular admissions, OFDMA sub-carriers, etc)

Digression: "Pay as you go" spectrum

- At start of a dynamic spectrum allocation (DSA) period, a "spectrum manager" auctions spectrum licenses
- Networks consider the interests of their active users and bid for spectrum
- Manager issues short-term licenses to each network
- At the end of a short period, all licenses expire and the whole process is re-initiated "from scratch"
- Above can be done "cell by cell" among CDMA networks by employing 2-layer spreading as in UMTS
- Doing so when non-CDMA networks are present is much trickier due to interference control
- Manager can arise from a "pooling" business model
- Several publications on this model are available (e.g., [8])

Auctions for medium access: Why?

- MAC auctions allocate channel to those that value access the most (“prioritised access”)
- A terminal’s valuation of access could either
  - represent the “true” “willingness to pay” of a user, or
  - be a “priority” index computed/adjusted by software
  - priority may be “adaptive”, depending on packet or application type, location, channel state, distance travelled, battery status, etc.
- Auction-based MAC is “incentive compatible”: needs not rely on “etiquette” or “altruism”

“sealed bid” MAC auctions

- Many possible auction formats
- A MAC auction should be relatively simple and fast
- Previous proposals resemble “sealed bid” auction
  - each bid is independently submitted in a “sealed envelope”
  - envelopes are opened simultaneously
  - highest bidder wins, and pays as specified by the rules.
- Problems with MAC sealed-bid auctions
  - require an auctioneer (controller)
  - require another MAC protocol to receive the bids.
  - With a large, variable no. of bidders, the bid protocol may
    - waste system resources, if contention-free, or
    - miss important bids, if contention-based (the highest-value terminals may be unable to make a bid)

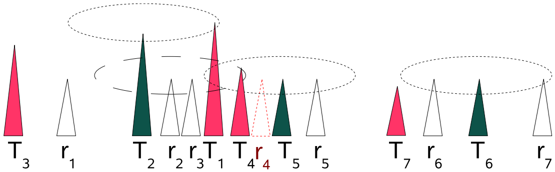
The Dutch auction for MAC

- How it works:
  - Public “clock” displays a progressively falling price
  - Participants silently watch and wait
  - Eventually participant that most values object “takes it”
- This auction retains simplicity and speed, and add
  - own bid-making protocol that prioritises highest bid(s)
  - the possibility of a distributive implementation (start times, initial price, and rate of decrease can be pre-specified; then a terminal can determine from own clock the auction status)
  - Confirmation of transmitter-receiver pairs, with smooth continuation if the pair is infeasible
  - exceptional signalling economy

Simple MAC for synchronised Ad Hoc Networks

- Synchronisation enablers: GPS, cellular and “cognitive” pilot signals, periodic connection to wired network, etc.
- General schedule
  - At t_0 1st auction starts at pre-specified price, and time-rate of decrease, and lasts τ
  - At $t_0 + \tau$ the first winner(s) use medium for T time units
  - At $t_0 + \tau + T$ another auction starts, etc
- 3 short messages necessary for successful winning
  - the winner sends its ID and that of the desired receiver
  - the receiver, if available, sends a short confirmation
  - the winner announces the successful pairing.
- If the transmitter-receiver pairing fails, auction continues
- The “tick” of the “clock” must allow the 3 messages[9]

MAC specific example



T_i	r_j	*bid*
1	1	10
1	4	9
2	2	7
3	1	6
4	3	5
5	5	4
6	7	3
7	6	2

Auction starts at price 11, falling 0,1 every ϵ. After10ϵ price is 10, T_1 sends "I take it", but r_1 is too far.10ϵ later, price is 9, and $T_1 \rightarrow r_4$ fails: r_4 is "asleep". At price 7, $T_2 \rightarrow r_2$ is set. 10ϵ later, r_1 declines $T_3 \rightarrow r_1$ because it knows about $T_2 \rightarrow r_2$. $T_5 \rightarrow r_5$ and $T_6 \rightarrow r_7$ are set. At price 2, r_6 declines $T_7 \rightarrow r_6$ because of $T_6 \rightarrow r_7$

MAC Implementation issues

- Distributed version requires a “common clock”, which may or may not be a major challenge
- Auctioneer (controller) can easily handle asynchronous terminals by announcing start, initial price and time-rate of decrease, and possibly broadcasting the new price at every “tick”
- Protocol parameters (initial price, rate of decrease, etc) should be “optimised”. Processing and signal travel time, clock “drift”, and “valuations” statistics should be considered
- Possibility of simultaneous “I-take-it” needs to be addressed

Possibility of “tied” winners

- If several “I take it” are simultaneously sent:
  - potential receivers won’t respond (unable to decode)
  - winners will ‘think’ receivers are unavailable
  - auction will continue
- Thus infrequent ties are harmless
- If the possible bids can be idealised as continuous random variables, then the probability of tied bids is negligible
- If bids depend on “channel state” the probability of consecutive ties by same terminals is negligible
- If valuations are “discrete”, say between 1 and M, then
  - at auction start, each terminal adds to “true” valuation a random number between $-\frac{1}{2}$ and $\frac{1}{2}$
  - probability that 2 terminals remain tied is negligible

Conceptual summary

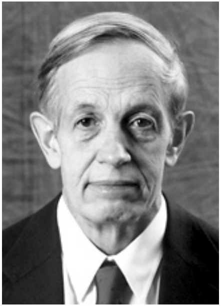
- A “free” economy is an example of a very complex system controlled in a mostly decentralised fashion
- Agents make local, relatively simple decisions following the rules, and complex system produces “reasonable” results
- Complex technological systems may be managed similarly
- Keys:
  - identification of the “agents”
  - specification of performance figures of merit
  - design of rules of interaction
- Economics provides an analytical foundation, and useful “algorithms”: markets, games, auctions and mechanisms
- We have seen the fruitful application of these ideas to several problems. Many other applications are possible

THANK YOU !!!

Vilfredo Federico Damaso Pareto

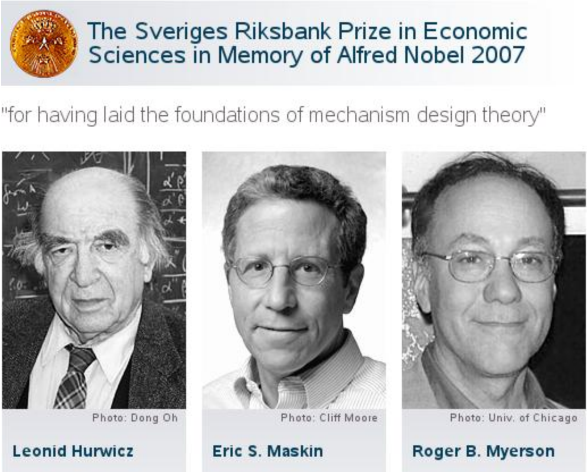
1848-1923. A Politecnico di Torino engineer who made important contributions to economics, sociology, and philosophy, he is best remembered for the concept of “Pareto efficiency”, a “base line” for resource allocation evaluation.

John Forbes Nash Jr.



Co-winner of the 1994 **Nobel Prise** for “pioneering analysis of equilibria in the theory of non-cooperative games". Best known for the Nash equilibrium, and the Nash bargaining solution. Popular book and movie “A beautiful mind” are based on his eventful life.

2007 Economics Nobel Laureates



William S. Vickrey

Co-winner of the 1996 **Nobel Prise** for "fundamental contributions to the economic theory of incentives under asymmetric information". Best known for his “truth-revealing” second-price auction.

Hal R. Varian

Recent Dean of the School of Information at Berkeley’s Haas School of Business, now Chief Economist at Google, Inc. Mentioned for his mechanism to achieve efficiency in the presence of mutual “interference”.

Ronald H. Coase

Winner of the 1991 **Nobel Prise** "for his discovery and clarification of the significance of transaction costs and property rights for the institutional structure and functioning of the economy".

Aalsmeer (NL) flower auction

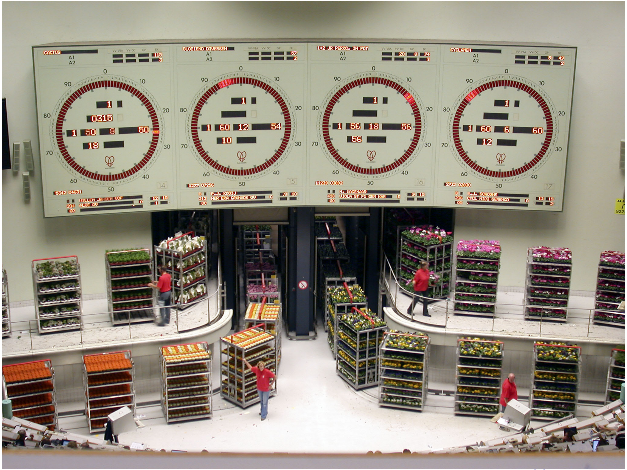
- Price clock starts at a “high” price, which progressively falls
- A bidder wishing to buy at current price, pushes a button to stop the clock, and uses microphone to indicate desired quantity
- Then the price clock moves to a slightly higher price, before resuming decreasing movement
- The next bidder who stops the price clock buys at current price, and so on until the complete lot of flowers is sold
- the auction then starts to sell another lot
- Prices form about once every 4 seconds on a clock

Facts and figures about Aalsmeer flower auction

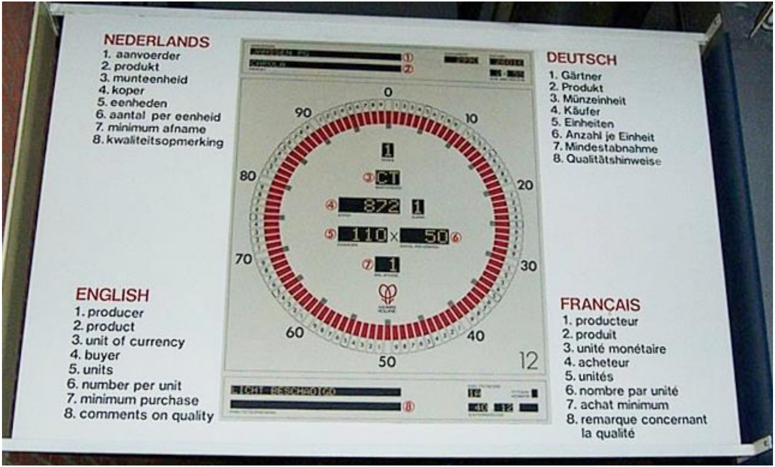
According to www.vba-aalsmeer.nl, in 2006 :

- Daily number of growers delivering products: $\approx$5.300
- Daily number of traders purchasing: $\approx$1.050
- Daily number of transactions: $\approx$44.000
- Transactions per clock per hour: $\approx$1.100
- Average daily turnover (auctioning): EUR 4,8 million
- Annual turnover: EUR 1,75 billion
- Size of auction complex: 1 million m^2 or 200 football fields (World's largest commercial building per Guinness)

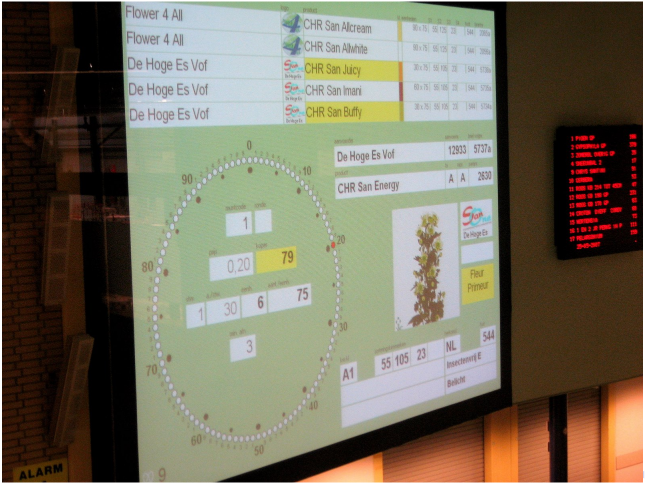
Traditional dutch clocks



Dutch clock (detailed view)



Dutch clock for image-based (remote) auctions



Dutch auction in progress

Aalsmeer, The Netherlands

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