Auction mechanisms for Network Resource Allocation

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University of Thessaly, Dept. Of Computer and Comm. Engineering

- Dept. belongs to school of Engineering, UTH
- Located in Volos
- Founded in March 2000, first graduates in 2005
- 20 tenure and tenure-track faculty members, 10 visitor instructors
  - > 500 undergrad, 40 grad students

Team

- Prof. Leandros Tassiulas (Head of Group)
- Iordanis Koutsopoulos (Asst. Prof.)
- Thanasis Korakis (Lecturer)
- 3 post-doc researchers
- ~15 graduate students

Projects on related themes

- OPNEX: FP7 STREP FIRE (coord.)
  - Optimization-driven Multi-hop Network Design and Optimization
  - Start from first principles optimization theory
  - Develop decentralized algorithms (from PHY to Transport)
  - Translate algorithms into implementable low-overhead protocols

- N-CRAVE: FP7-ICT-2007-1, Network of the Future, STREP (coord.)
  - Network Coding for Robust Architectures in Volatile Environments
  - Novel protocols based on Network Coding (access to application)

- CONECT: FP7 STREP FIRE (coord.)
  - Cooperative Networking for high capacity transport architectures
  - Leverage cooperation at signal and access level for video multicasting over wireless

Projects on related themes (2)

- NADA: FP7 STREP FIRE
  - Nano-data centers
  - Develop new peer-to-peer network communication paradigm for content delivery and distributed storage

- NEWCOM++ and EuroNF NOEs
  - Network Theory
  - Scheduling and adaptive RRM, traffic engineering

- ONELAB: FP7 IP FIRE
  - Develop a federation of experimentation test-beds
  - Remote capability of experiments
  - Inter test-bed coordination framework

Main Research Topics

- Network information theory and network control
- Cross-layer network design and optimization
- Energy efficient designs in wireless networks
- Peer-to-peer networks performance evaluation
- Sensor networks
- Implementation of wireless protocols on the NITOS test-bed

This presentation

- Brief Primer of Auction Mechanisms

1. Outline structure of basic auction models
2. Give flavor of more composite models
   - Sponsored search auctions in internet ads
   - Issues arising in spectrum sharing in cognitive radio networks
3. Delineate main trends and brainstorm in future challenges
   - Advanced auction models that capture multi-level interaction of entities
   - Double auctions for multiple seller – buyer interaction
   - Decentralized negotiation / resource trading mechanisms

Future Networks

- Future networks: diverse interacting rational entities with natural inclination to solicit own objectives
  - Misreporting of utilities, declaration of higher needs, selfishness, abstaining from contributing resources to network, …
- Need for decentralized network control
  - Self-management, autonomous resource trading, …
- Match unpredictable supply and demand profiles
  - Varying spatiotemporal patterns, volatility, intermittent availability
  - Need for online resource sharing, flexible allocation of resources
- Control decisions to be taken under partial or no knowledge of network state
  - Cost for obtaining feedback
  - Rapid topology / load changes, interference
  - Perfect state may be infeasible or meaningless to have

Future Networks (cont.)

- Internet architecture: federation of elements coming into spontaneous interaction
- Recent regulatory developments (e.g. spectrum liberalization) in favor of ad-hoc interaction, impose market point of view in resource allocation
- Each entity possesses an amount of resource:
  - Resources brought to common pool, from where a resource allocation regime has to emerge
  - Different twists, depending on resource

Various network instances

- Wireless ad-hoc:
  - Forward (own or others') data to next hop with limited Energy and/or Bandwidth
  - Enforce cooperation regime such that total cost is minimized
- Interference-limited links:
  - Allocate transmit power
  - Maximize sum of coupled (due to interference) utilities
- Peer-to-peer:
  - Peer access link bandwidth shared between upstream / downstream
  - Achieve socially optimal operating point (sum utility maximization)
- Disruption tolerant (intermittently connected):
  - Store content in cases of no connectivity, forward if allowed to
  - Allocate cache memory or disk space to sporadic requests and own content)
  - Maximize utility or minimize delay in end-to-end data transfer

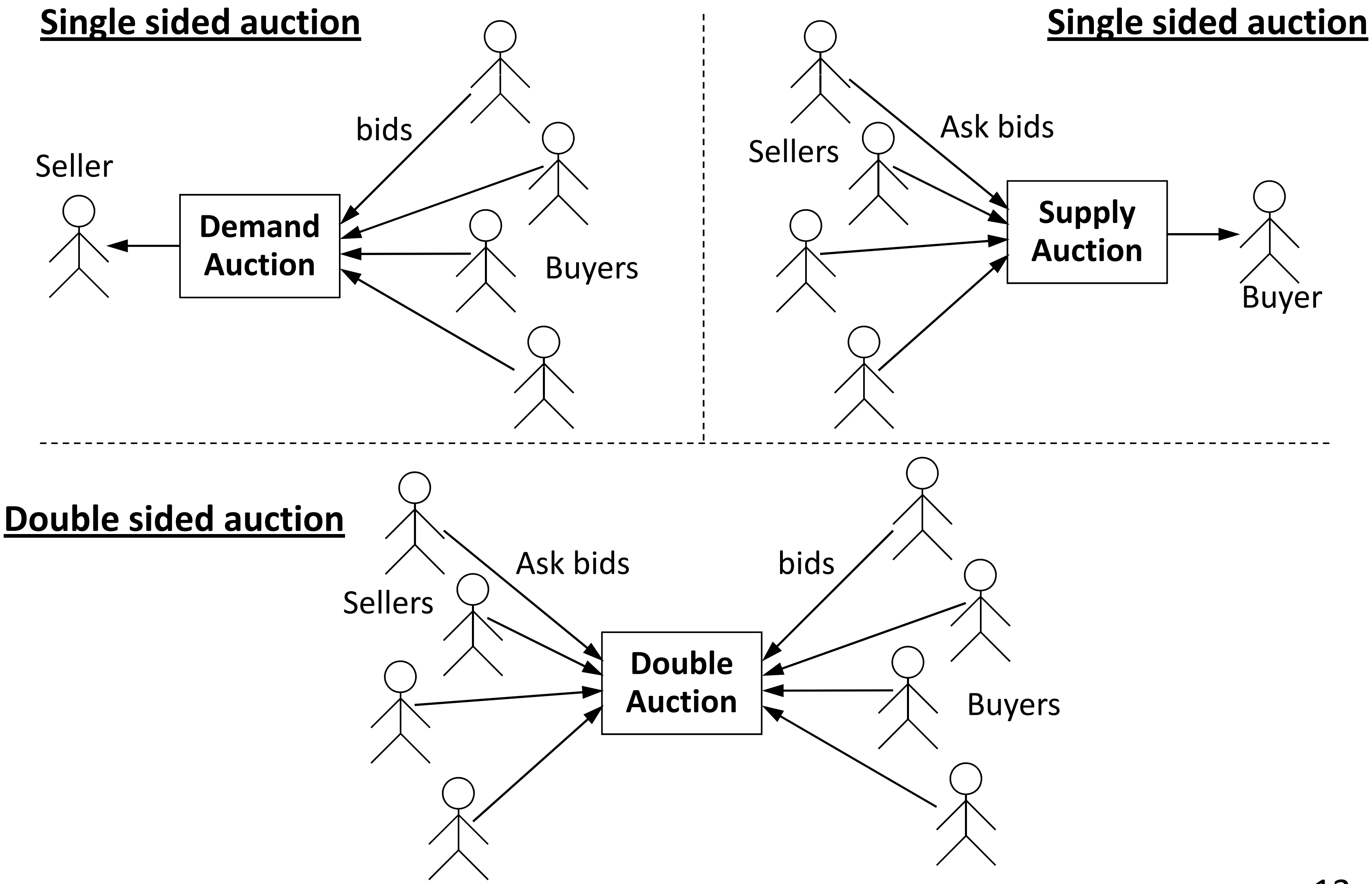
Various network instances (cont.)

- Cognitive radio:
  - Portions of spectrum chunks to be allocated among primary / secondary providers and / or users
  - Maximize revenue of providers, optimize spectrum utilization (reach socially optimal allocation)
- Virtualized server configurations:
  - Bottleneck resource : CPU
  - Migrate application processes from machines they actually run on to virtual machines
- Decentralized data centers:
  - Data center storage space shared among competing agents
  - Minimize retrieval delay, data transfer delay

Auctions

- Auction instances (to sell)
  - One indivisible item to be allocated to one among several buyers
  - Multiple indivisible items to be allocated to buyers
  - Divisible good of quantity C to be allocated among buyers
- Each buyer characterized by utility function (valuation)
- Most common objectives
  - maximize auctioneer revenue
  - maximize allocation efficiency (social welfare)
- Main attractive feature: achieve desired resource allocation while agnostic to utility functions
  - limited / distorted state information
  - varying demand / supply
  - diverse, conflicting user interests
  - utility function cannot be precisely captured / determined

Basic Auction Types



More on basic auction structure

- Good to be allocated to multiple buyers
- Each buyer characterized by a utility (valuation) function, not known to auctioneer and to other buyers
  - satisfaction as function of quantity of good (good divisible)
  - satisfaction from obtaining item (good indivisible)
- Buyers submit bids to auctioneer
- Auctioneer maps bid vector **b** to vector **x** of allocated quantities and vector of payments **p** for each user
- Objectives of resource allocation:
  - maximize social welfare (sum of utilities)
  - Maximize revenue

More on auction design objectives

- A. Maximize incurred revenue for seller
  - Increase competition, induce bidders to participate, bid high
  - Increase expected price at which item is sold
- B. Maximize Efficiency of allocation
  - 1 item: allocate it to bidder who values it most
  - Multiple indivisible goods or divisible good: maximize social welfare
- A, B may be conflicting
- C. Fairness: w.r.t. to properties of utility vector
- D. Promotion of truthful reporting of valuations
- E. Discouragement of collusion
- F. Simplicity of mechanism, …

Single-item auctions

- A seller to allocate an indivisible item to one out of N buyers
- Each buyer i knows only own valuation u_i of item, auctioneer knows none of valuations (private value auction model)
- Class of Open-type auctions
- Ascending price (English):
  - Auctioneer starts by announcing a low price, keeps increasing it as long as there exist at least two interested parties
  - (Or bidders may bid higher and higher)
  - Auction stops if *one* interested bidder remains
  - That last bidder obtains item, pays amount equal to *price at which second-last bidder dropped out*
- Descending price (Dutch):
  - Auctioneer starts by announcing a high price, keeps decreasing it until the first bidder declares interest at that price
  - That bidder takes item, pays amount *equal to that price*

Single-item Auctions (cont.)

- Class of Sealed-bid auctions
- Sealed-bid first-price auction
  - Bidders submit bids in *sealed* envelopes
  - Bidder with *highest* bid wins item, pays amount he bid
- Sealed-bid second-price auction (Vickrey)
  - Same, but highest bidder pays *second-highest* bid
  - Truthful declaration of valuation: no incentive not to bid true valuation
  - For any configuration of competing bids, bidder either loses in net payoff or does not gain anything from bidding $b_i \neq u_i$
- Under private value model:
- Open Dutch auction equivalent to Sealed-bid first price auction
- Open English auction equivalent to Vickrey auction

Risk Averseness vs. Risk-neutrality

- Risk-averseness (neutrality) -> concave (linear) utility function
- Risk-averse seller
- Say auction runs many times, item sold at price p_i at i-th time
- $E_P[U(P)] \leq U(E[P])$
  - Average utility from repeating auction (with different payments) less that utility at average payment
  - Payment variability around mean reduces utility
  - Seller prefers auction with more balanced payments, even if this leads to smaller average payments
- Risk-averse bidder
- Similar definition, for average net benefit (average over bidding)
- Risk-neutrality
  - Variability around mean does not reduce utility
- Expected seller revenue (expected payment) is the same for first- and second-price auctions (Revenue Equivalence principle)

More Taxonomy

- Private valuations: bidder knows only its own valuation
  - If a statistical model used, bidder knows probability distribution of own valuation and of others
  - Knowledge about others' valuations does not affect own
- Interdependent valuations: bidder has full or partial information about own valuation
  - Its valuation affected by information available from others
- Multi-object auctions
- Homogeneous (multi-unit) vs. heterogeneous
  - Homogeneous: uniform-price / discriminatory-price
- Sequential vs. simultaneous
- Individual vs. combinatorial

Auction mechanisms for Divisible resources

- Divisible good C to be allocated to N users
- User i : utility function $U_i(x)$
- Social Welfare Maximization problem (SWM)

$$\max_{\mathbf{x}\geq 0} \sum_{i=1}^{N} U_i(x_i)$$

subject to:

$$\sum_{i=1}^{N} x_i = C\,.$$

- If utility functions were known by controller:
  - SWM solution: x_i^* is such that: $U'_i(x_i^*) = \lambda$, $x_i^* > 0$, and $U'_i(0) \leq \lambda$.
- Challenge: controller does not know utility functions, aims at socially optimal allocation
- Class of allocation mechanisms where each user submits bid b_i for amount he is willing to pay, and charged according to function c(.)
- Allocated amount: $x_i(b_i) = b_i/\lambda$: λ price per unit of resource

Kelly mechanism

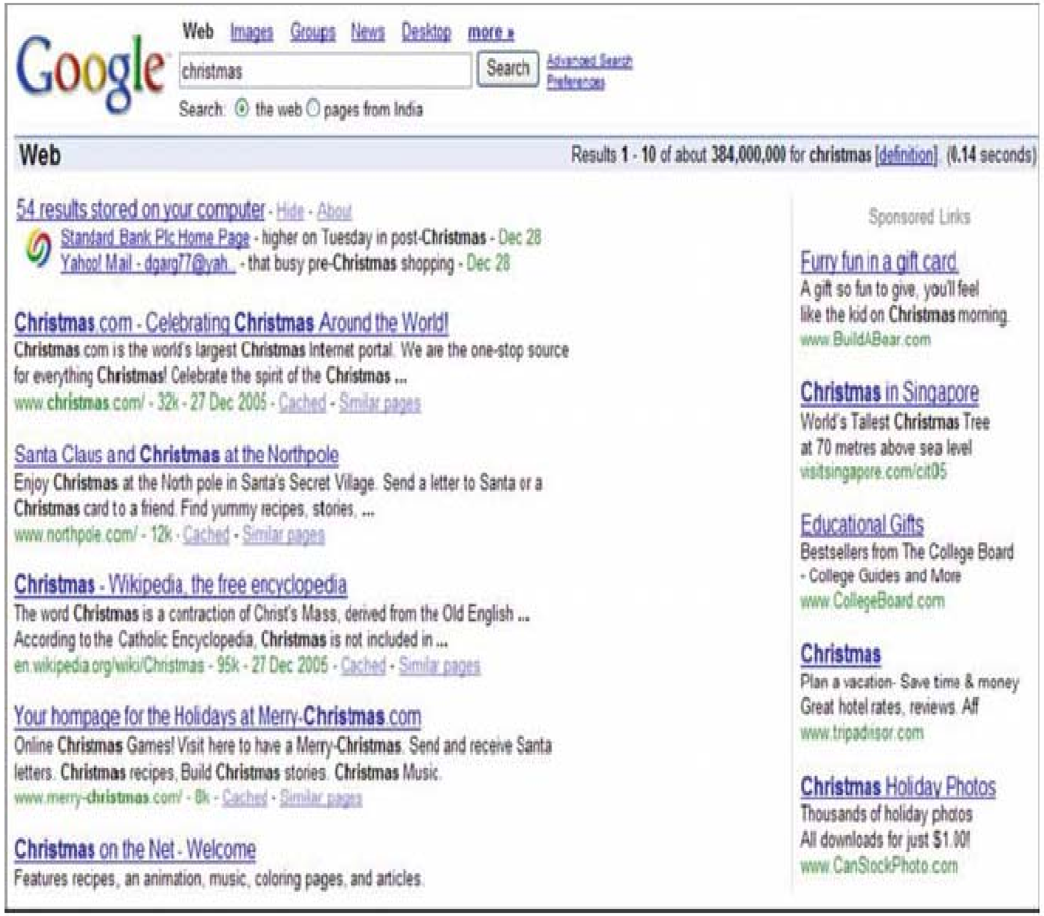
- Price-taking users: not anticipate impact of bid on price (charge function)
- Rational bidders: cast bid to maximize net benefit: $U_i(x_i(b_i))-c(b_i)$
- Say, given the bids, auctioneer solves problem (P):
- $\max_{\mathbf{x}} \Sigma\, b_i \log x_i$ s.t $\Sigma x_i = C$ (P)
- Turns out that if charge function is $c(b) = b$, solutions of problems (P), (SWP) coincide
  - so are Lagrange multipliers (equal to $\Sigma_i\, b_i / C$)
  - Proportional allocation optimal: $x_i = b_i\, C / \Sigma_i\, b_i$
- Kelly ('98): Iterative decentralized approach
  - Market price computed by auctioneer from dual problem (increases or decreases it, based on bid demand)
  - Users adjust bids based on price
- Price-taking users: one-dim bidding and appropriate charging suffice for socially optimal allocation

VCG Mechanism

- Price-anticipating users: strategically adapt bid, consider impact on price
- Efficient (socially optimal) allocation : VCG mechanism
- Bidders requested to reveal utility functions $U_i(.)$
- User i bid is a function $b_i(x)$ of amount of resource x
- Amount charged to each user: externality caused to others
  - Total utility reduction caused by presence of i to all others
- Desirable properties
  - Efficiency of allocation
  - Truthful reporting of utility is best for each user
  - *Undesirable: huge complexity
- VCG-Kelly type mechanisms proposed (Hajek, Johari, Tsitsiklis)
  - 1-dim bids, proportional allocation, charging as in VCG
  - Efficient allocation, but lose property of truthful utility reporting

Sponsored Search Auctions: internet ads

- Auctioneer: search engine
- Bidders: advertisers, wishing to have their ad appear on user's search screen after search
- Ads appear in ranked list
- User clicks on ad and is taken to respective site
  - Advertiser pays search engine for that
  - Each time a user clicks on an ad
- Ad positions (rank slots) are auctioned
  - The higher the rank of an ad, the more probable that ad will be clicked on by a user



Sponsored Search Auctions (cont.)

- Ad auctions: auctioneer revenue / bidder payoff depend on internet user satisfaction
- N advertisers bid for K < N ad positions
- b_i: bid per click of advertiser i
- CTR_{ij}: probability that i's ad clicked when in position j (obtained through historical data)
- $CTR_i = \Sigma_j \, CTR_{ij}$ x Prob(ad i displayed in position j)
- <u>AUCTION</u>
- Advertisers bid b_i
- Google makes ad appear in slots in decreasing order of $b_i \times CTR_i$
- Advertiser in k-th position with $b_{(k)} \times CTR_{(k)}$ pays $b_{(k+1)} \times CTR_{(k+1)}$
- Payment per click: $p_{(k)} = b_{(k+1)} \times CTR_{(k+1)} / CTR_{(k)}$
- Known as Generalized Second Price (GSP) auction

Spectrum auctions

- Dynamic spectrum access / spectrum sharing
- Licensed spectrum bands of Primary Operator (PO)
- Coordinate unused spectrum leasing to Secondary operators (SOs)
  - SO: local one, smaller range operator
  - SOs further allocate spectrum to secondary users
- Utility derived difficult to estimate
  - Depends on unpredictable demands, availability, channel quality, geographical range of SOs, interference, channel sensing inaccuracies, …
- Spectrum reuse by operators or users at far away locations
  - Interference restricts set of feasible channel allocations
- Spectrum bands differ in quality (reuse, fading, freq. selectivity)
- Heterogeneity, unpredictability of demands, mobility
- Online fashion of allocation

Future Direction 1: Advanced Auction Models

- Example: Multi-tier model

- Primary Operator → Secondary Operator → Secondary User

- Are conventional auction models sufficient?
  - SOs bid, PO decides allocation + payment, done
  - Probably not…
- Appropriateness of frequency allocation from PO to SO depends on experience of secondary user, served by SO
- Not good for a PO to allocate a frequency to SO that will allocate it to a user for which frequency is of low quality (due to interference, limited SO range)
  - End users served by SO most likely are clients of PO as well!

Future Direction 1: Advanced Auction Models (cont.)

- Primary Operator → Secondary Operator → Secondary User

- Consider feedback from end-user (secondary user) substrate (besides PO valuations)
- Spectrum allocation : modulate SO bid with end-user (secondary user) experience
- End-users satisfied and willing to use PO for other services
- PO benefits as users choose him and not other POs

- Connection with sponsored auctions in internet ads?
  - Ongoing work towards this direction

Future Direction 2: Double Auctions

- Each entity possesses resource, engages in transactions
  - Different needs, different utilities
- Resource exchange in market style among resource providers and consumers
- Providers with excess spectrum (or other resource) may sell to other providers in need of resource

- Bird's eye view: match spatiotemporally varying demand and supply patterns
- Microscopically: double auctions
- Buyers contend to obtain resources by placing bids to several sellers
- Sellers announce ask bids at which they sell
  - Multi-lateral transactions

Future Direction 2: Double Auctions (cont.)

- Multiplex supply and demand in space and time to achieve best resource utilization
- Derive allocation and payment rules for selling and buying resources
- Multiple sellers and buyers: objective ?
  - Maximize revenue for all would lead to tragedy of commons
  - Various properties of network operating points
- Resource reciprocity mechanisms
- Interdependent resource provider and consumer role
  - E.g. in peer-to-peer networks, link capacity used either for download or for upload
  - Client role places restrictions to the other (server) role!
  - Ongoing work: substitute role of auctioneer with distributed approach

Future Direction 3: Negotiation and Trading

- Negotiation among different entities
  - cooperative entities that accept to negotiate
  - entities have conflicting interests
- Goal: reach mutually desirable allocation regime
- An entity attempts to affect outcome by making offers to others
  - Other parties may accept offer, reject offer or make alternative ones
- Issue: available information at an entity about other entity
- A framework for negotiation and resource trading for networks?

- THANK YOU !