WP5 : Auction-Driven Dynamic Spectrum Allocation

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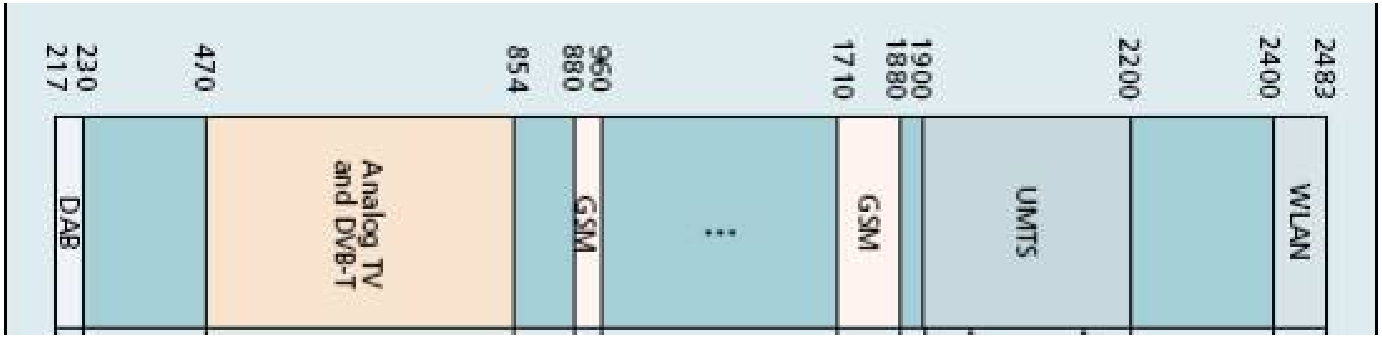
Overview

- Dynamic spectrum allocation adjusts the allocation as needs change in time and space. We implement DSA by periodically auctioning licenses all of which expire in a short time.
- Current spectrum licensees can adopt our scheme under a “resource pooling” business model, involving an intermediary.
- A current licensee with several radio technologies (telephony, digital TV, etc) could adopt our scheme to dynamically allocate its private spectrum internally among its own divisions.
- Below, terminals with dissimilar data rates, channel states, and “willingness to pay” download data in a CDMA cell.
- We provide crisp analytical results applicable to many physical layers: revenue-maximising prices, an optimal operating point, a “revenue per hertz” priority, and a simple bidding strategy.
- In our horizon is a similar analysis for a digital video broadcast situation

Outline

- Current spectrum allocation and its problems
- Dynamic Spectrum Allocation (DSA) as a solution
- Our approach to DSA vs previous work
- Business model and key questions and answers
- A second-price auction
- Optimal pricing
- Optimal bidding
- Conclusions and next steps

Spectrum Allocation Now



- **Available spectrum is split in bands allocated to specific radio-access technologies (RAT) (DVB-T, UMTS, etc)**
- **Some bands are left “open” (license-free) (e.g. WLAN)**
- **Most bands are further divided and allocated (by auctions, “beauty contests”, lotteries, etc) to specific entities for exclusive use for a “long” time (e.g. 20 years)**
- **License transfers/trading are generally restricted**
- **Spectrum allocated to a RAT typically cannot be used for another**

Problems with technology specific allocation

- Spectrum allocation to radio access technology (RAT) is based on long term forecasts (wild guesses?)
- Public acceptance of new technologies may grossly exceed or fall way short of original expectations
- Also, a formerly popular RAT may fall from favour (paging, UHF TV, etc)
- At specific time and place, a RAT may be in very high demand, while another is lightly loaded
- Some technologies consistently have opposite “busy hours”: when one is in high demand the other isn’t (e.g., mobile telephony vs digital video entertainment services)

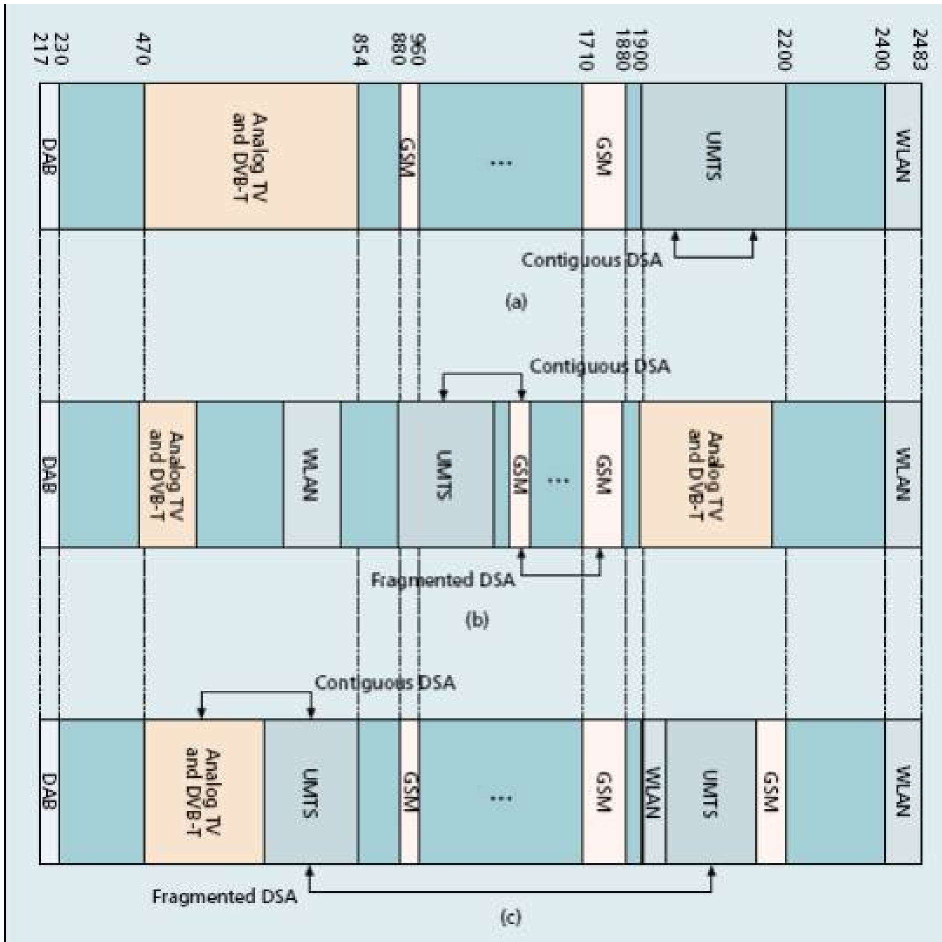
More problems with current spectrum allocation

- Even within a given radio access tech., radio-access networks (RAN) may face dissimilar demand for services
- The market share of a RAN may not match its original spectrum allocation (long term forecast may be wrong)
- Market share may vary from a place to another, and from a time to another, while spectrum shares remain fixed
- Regardless of market shares, random events can make a RAN considerably busier than others at specific instants
- License trading could remedy some of the long term imbalances, but not the short term ones.

Possible Solution: Dynamic Spectrum Allocation (DSA)

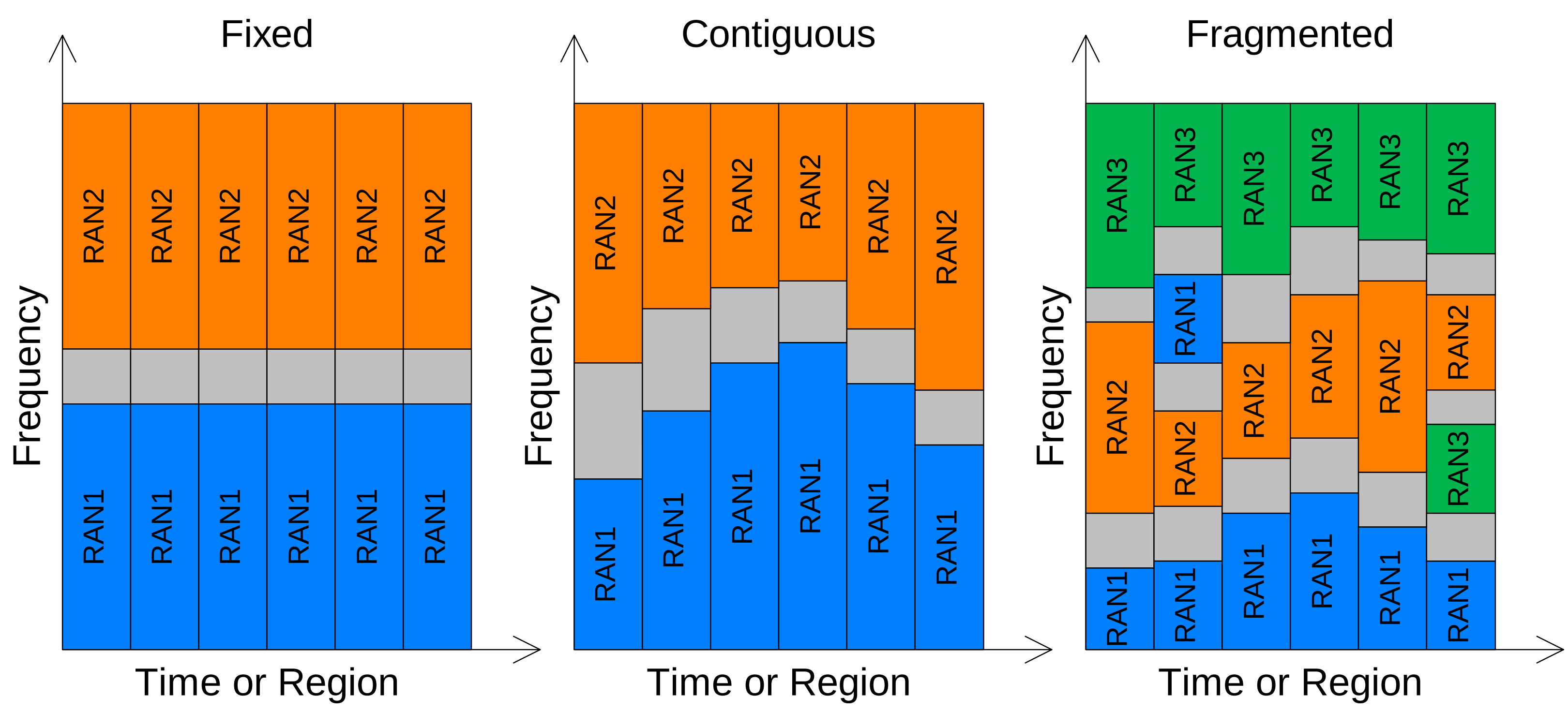
- DSA allocates spectrum on short term basis, trying to match the allocation to actual "needs" at a time and place
- [1] P. Leaves, et al., "Dynamic spectrum allocation in composite reconfigurable wireless networks," (*IEEE Comm. Mag.*, v. 42 pp. 72–81, 2004) reports recent work
  - ⇒ A spectrum manager performs DSA (every 30-60 minutes) without any monetary/business concerns
  - ⇒ One UMTS and one DVB-T operator participate
  - ⇒ Simulation gains approaching 40% reported
- Current networks and standards do not support DSA, but necessary functionality appears within reach
- Business issues are key, because a lot of money has already been paid for long-term spectrum allocations

Spectrum: Now (top) vs Future (at a time and place)

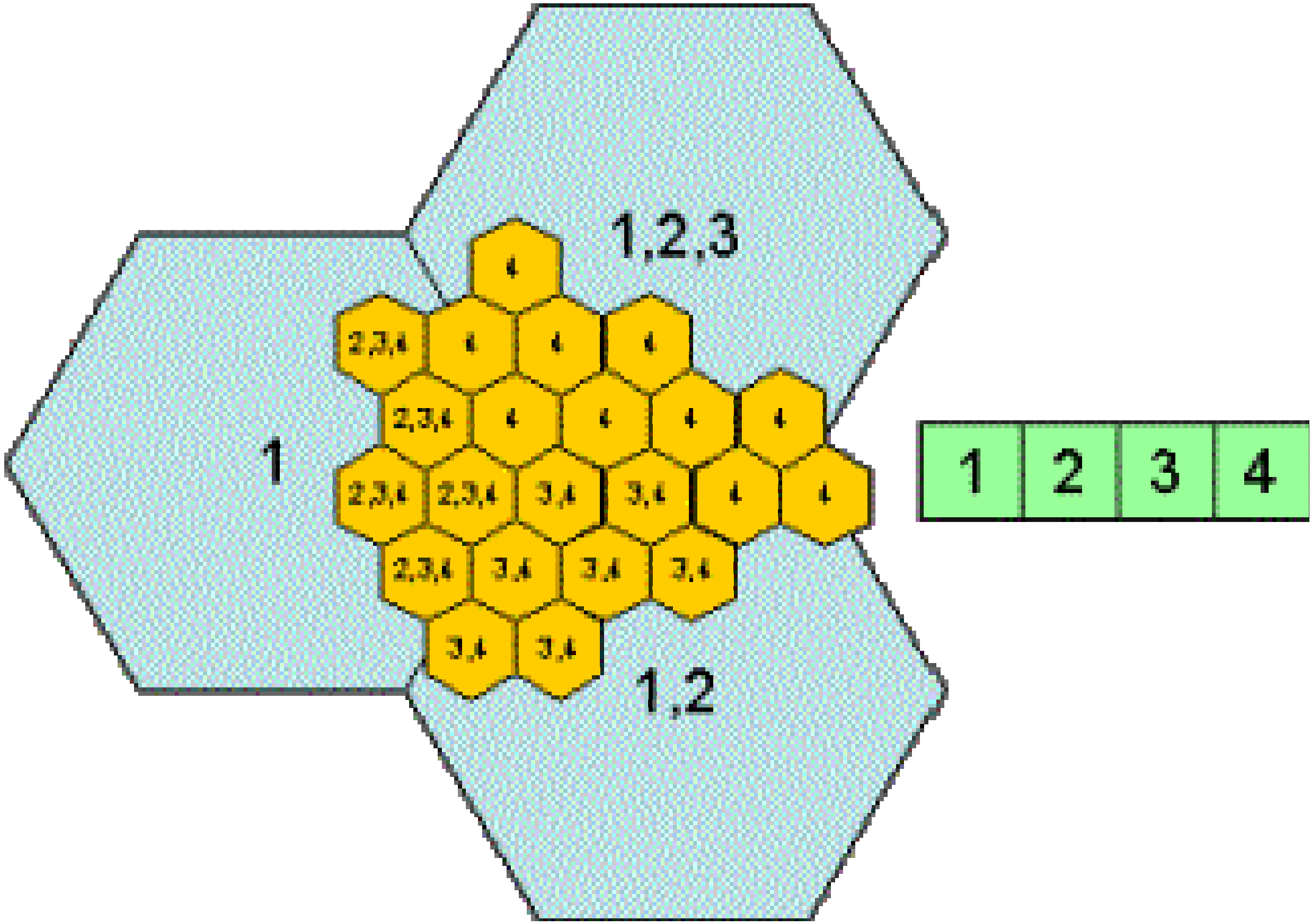


- From Reference [1]

Spectrum allocation: DRIVE & overDRIVE projects



DSA from region to region



- 4 bands for 1 UMTS and 1 DVB-T (large cells) operator. To the left, DVB-T has only one band. At the top DVB-T has bands 1, 2 & 3

Our DSA Approach

- Decentralized (operator "chooses" own allocation)
- Pricing (market) Driven
- Basic idea: "pay as you go" spectrum
  - ⇒ At start of a DSA period, a "spectrum manager" "sells" (auctions?) spectrum licenses
  - ⇒ Network operators consider the interests of their active users and purchase (bid for) spectrum
  - ⇒ Depending upon the purchase orders or bids, manager issues short-term licenses to each operator
  - ⇒ At the end of a short period, all licenses expire and the whole process is re-initiated again

Possible Business Model

- Licensed operators create a spectrum management firm to be owned by the operators themselves
- They transfer their current licenses to the new firm. Firm pays them with “shares” based on amount of contributed spectrum
- Spectrum management firm leases the participating operators (and anyone else they approve) the spectrum they need for short term use
- Firm utilizes some economic mechanism (auction?) agreed upon by all parties to allocate short-term spectrum licenses.
- The firm’s profits are eventually shared among the shareholders (the original spectrum licensees)
- State agency may want to regulate managing firm for antitrust purposes (consumer protection/monopoly/fairness issues)

Some Key Questions

- "Guiding principle": efficiency, fairness, revenue?
- Economic mechanism to allocate short-term licenses: simple unit pricing, nonlinear pricing, auctions?
- If an auction, which format: "sealed bid" vs "open outcry", winner pays own bid vs a function of "losing bids", multi-round vs. direct, "complex" auction vs traditional/common one, etc., etc.
- Different auctions are more or less vulnerable to "malicious" behaviour… which counter-measures?
- License expiration: the shorter the time the most efficient the DSA, but the greater the disruption to networks

Possible Key Answers

- If managing firm is owned by the original spectrum licensees, profit maximisation seems reasonable (makes possible new entrants). For state agency, efficiency/fairness issues seem more important. Our scheme works either way
- Auctions seem reasonable economic tool, currently in actual use for spectrum allocation by state agencies (e.g. EU, USA)
- Because DSA auctions are to be repeated within short time (minutes?) they must be “direct” (one or very few rounds). A computerised procedure implementing a “sealed bid” auction format seems appropriate
- counter-measures to “malicious” behaviour as appropriate for chosen auction format
- License expiration to be determined mostly by technology: the sooner the better, but network reconfiguration may be tricky

Present vs previous work

	This Work	Previous Work
General approach	Decentralised: operator "chooses" allocation via econ. tools (bids, etc)	Centralised:"manager" allocates spectrum w/o business concerns
Data Services	Multi-rate CDMA on UMTS	No, Voice-only UMTS
Video Services	On DVB-T & UMTS (future)	Only on DVB-T
Physical layer; Resource management	Considered (data rates, power, channel gains, etc). Generalized channel model	Not considered (e.g., a UMTS band always holds a fixed # of calls)
Value/importance of service to user	Considered (β_i)	Not considered
Methodology	Analytical/simulation	Simulation only

Scenarios to be analysed

- **One cell with 2 CDMA operators (unequal loads)**
  - ⇒**data only**
  - ⇒**Media (video) and data terminals**
- **Same operators as above, in a 2-cell system; different loads per operator per cell**
- **A DVB-T operator enters previous scenario. DVB-T cell overlays BOTH UMTS cells**
- **Previous scenario extended to entire 1-dimensional topology**
- Below: only the downlink of first scenario is discussed

Vickery (2^{nd} Price) Auction

- Suppose that for chosen auction format, it is optimal for each bidder to bid "truthfully" (a bid for a certain amount of spectrum equals the revenue that it would yield)
- The Vickery (2nd price) auction is an example of such format. For a single object, it works as follows
  - ⇒ The bidder submitting the highest sealed bid wins
  - ⇒ Winner's payment equals highest LOSING bid
- Intuition: suppose you bid what the object is worth to you:
  - ⇒ If you win, a lower winning bid by you would NOT have lowered what you pay : the highest LOSING bid
  - ⇒ If you lose, bidding higher to win would mean paying more than the object is worth to you. Why would you do that?!

Multi-unit Vickery Auction

- Divide the available spectrum into K (say 3) “bands”
- Assume bands are identical for considered technologies
- A bid is a K-dim vector (b1,b2,b3) meaning
  - ⇒ I offer b1 for a total of one band (whichever one)
  - ⇒ I offer b1+b2 for a total of two bands (whichever)
  - ⇒ I offer b1+b2+b3 for all 3 bands
- One band goes to the bidder submitting highest overall bid, the next band goes to the bidder submitting the second highest bid (looking component by component), etc. Several (all) bands could go to same bidder.
- Payment: a winner of k bands pays the sum of the k highest LOSING bids submitted by others

Multi-unit Vickery Auction: Numerical Example

- Assume 2 bids are submitted: B1=(5,3,2), B2=(4.5,4,1)
- Allocation
  - ⇒ One band to bidder 1 (5 is top bid)
  - ⇒ Next band to bidder 2 (4.5 is second-highest bid)
  - ⇒ Last band also to bidder 2 (4 is next highest bid)
- Payment
  - ⇒ Bidder 1 got one band, and must pay highest LOSING bid submitted by bidder 2, which is 1
  - ⇒ Bidder 2 got 2 bands, and must pay sum of 2 highest LOSING bids from bidder 1, that is, 3+2=5
  - ⇒ "System" gets 1+5=6

CDMA Operator's problem

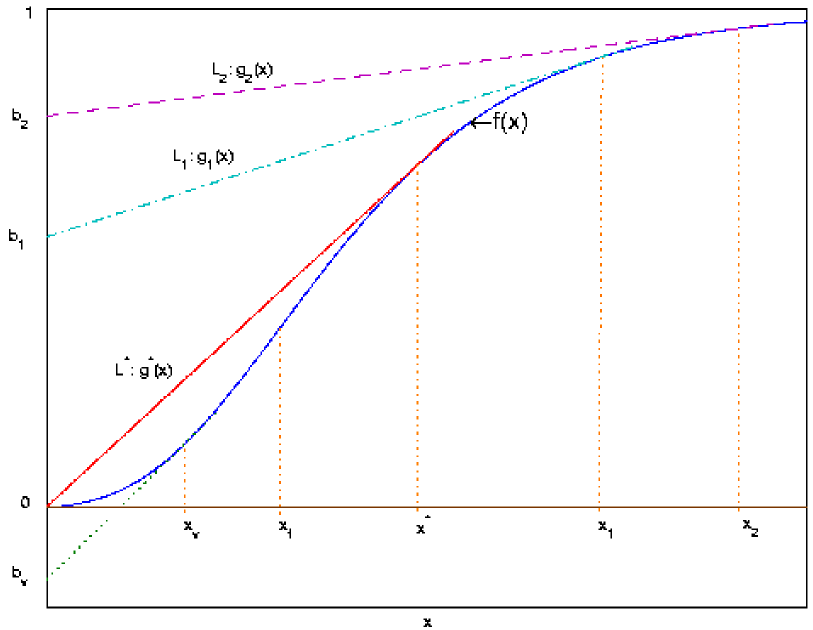
- Given a set of "users" (data, possibly video) what is the "optimal bid" for a given amount of spectrum
- For the chosen auction, the operator's optimal bid equals the maximal revenue obtainable from the given band
- The revenue depends on the operator's own (internal) pricing policies: the higher the price the lesser the demand for services
- Also, a higher demand requires more spectrum
- Impact of pricing on resource usage (e.g., power) should also be considered, because for a given "load" the least efficient operator needs the most spectrum

Operator’s problem (2)

- CDMA Operator’s approach: use pricing to generate revenue AND to encourage efficient resource usage
- Assume simple linear pricing:
  - ⇒Terminal pays cx
  - ⇒x is received SIR (“quality of service”)
  - ⇒Terminal enjoys constant SIR over reference period

Model of physical layer

- Terminal's performance depends on physical layer (modulation, FEC, diversity, etc)
- Frame-success rate function (prob. packet is correctly received given SIR at receiver) is key
- Example given for non-coherent FSK, no FEC, 80-bit packet, independent bit errors
- On downlink, intra-cell interference can be neglected or included with noise term (σ^2)
- SIR: $x=GQ/\sigma^2$; G: spreading gain, Q=hP ; P: power, h: channel gain



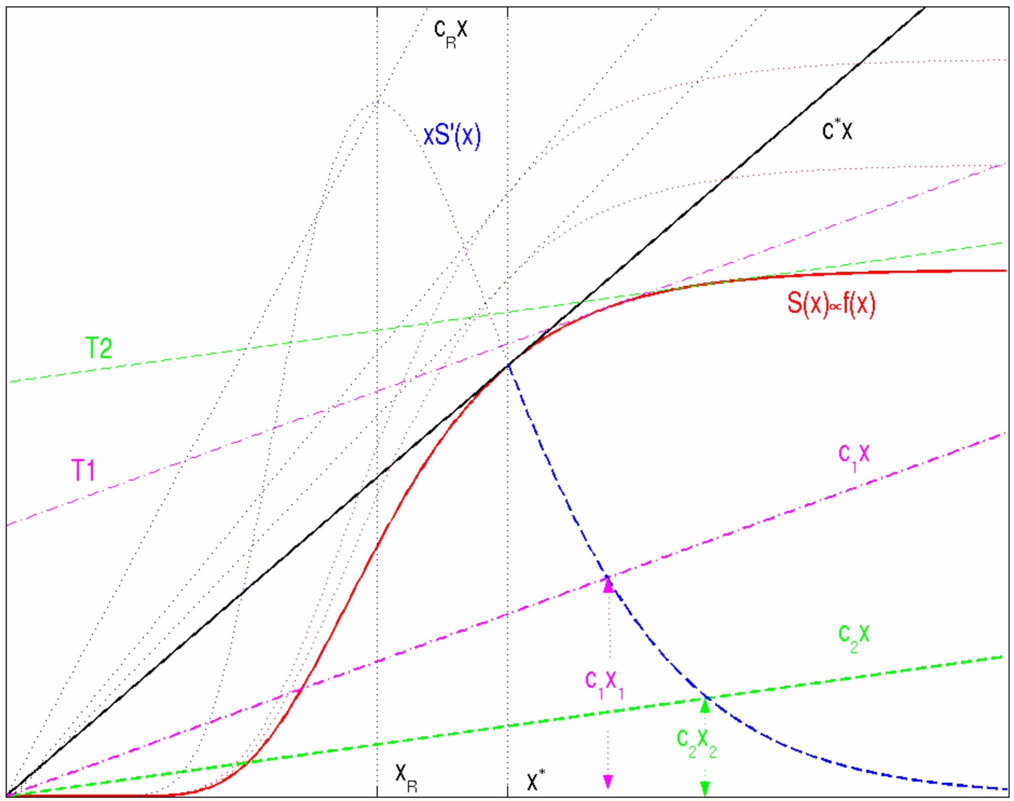
$$f(x) = \left[1 - \frac{1}{2}\exp\left(-\frac{x}{2}\right)\right]^{80}$$

$$x = G\frac{hP}{\sigma^2}\ ;\ G = \frac{w}{R} = \frac{\text{bandwidth}}{\text{data rate}}$$

Data Terminal Problem (1)

- Given pricing structure (linear), terminal must choose power to maximize "utility".
- For downlink, assume utility of the form $\beta_i B_i + y_i$
  - ⇒ B_i: # of bits correctly transferred in reference period, τ
  - ⇒ β_i: monetary "value" to terminal of 1 correct bit
  - ⇒ y_i: money left to consume "everything else"
- With L info bits per M-bit packet, $B_i = \tau(L/M)R_i f(x)$ where
  - ⇒ R_i is the data rate, x is received SIR
  - ⇒ $f(x)$ is frame-success rate
- All we know about f is that it is an S-curve
- Terminal will choose x to maximize $S(x)-cx$ where S is an S-curve (because B_i is proportional to f(x))

Maximizing S(x)-cx

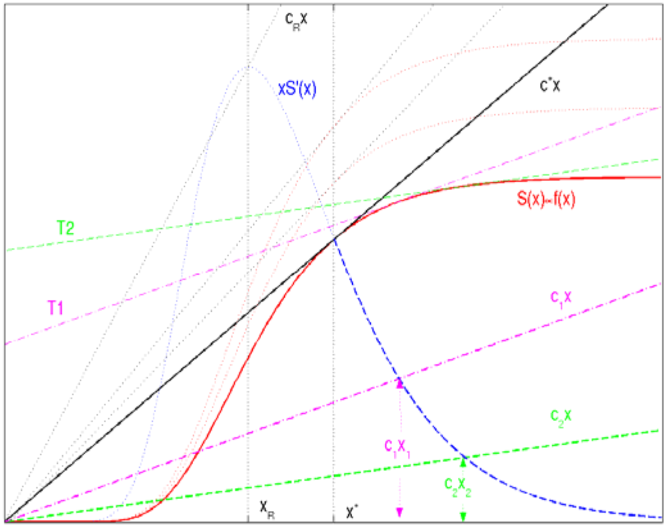


- Explained further below

END-TO-END RECONFIGURABILITY

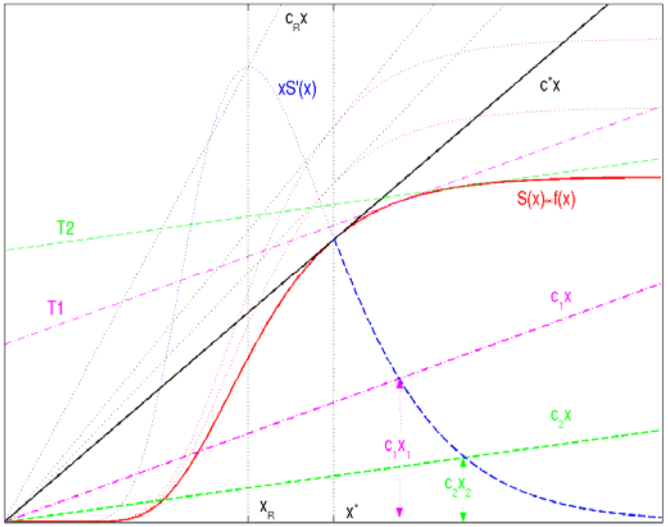
Terminal's choice: optimal SIR for given price

- Terminal converts price per Watt to price per SIR (x)
- if cx > S(x) for any x>0 terminal chooses x=0
- Highest acceptable price is c^* : slope of tangent from origin to S(x)
- for $c_1 < c^*$, it chooses largest x_1 s.t. $S'(x_1)=c_1$ (tangent at x_1 *is parallel* to line c_1x)
- operator's revenue is then $c_1x_1 = x_1{*}S'(x_1)$



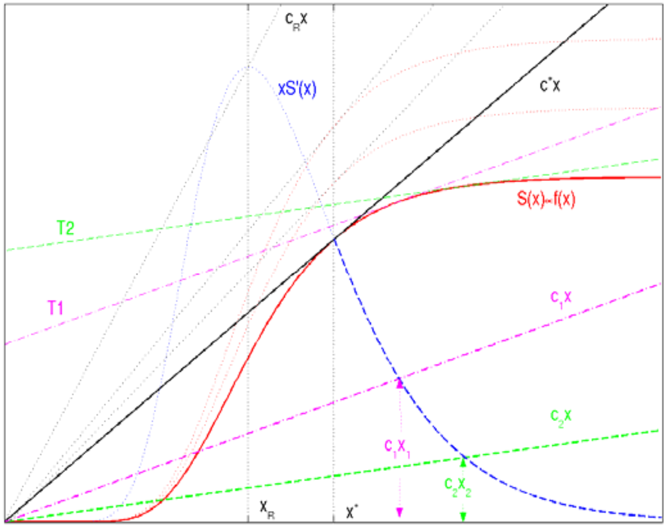
Operator's choice: revenue-maximizing price

- For $c_1 < c^*$ terminal chooses x_1 such that $c_1 x_1 = x_1 S'(x_1)$
- the curve $x^*S'(x)$ is single peaked, and for $x > x^*$ ($c < c^*$) has a maximum at $x = x^*$
- Thus, operator sets price so that terminal chooses $x = x^*$
- With L info bit in an M-bit packet, revenue equals $S(x^*) = \tau(L/M) f(x^*) \beta R$



Operator's choice with many terminals

- Operator will set individual prices s.t. i pays SIR at price c_i^* (tangent from origin to S_i)
- All $S_i(x)$ are multiples of f(x), therefore, all share x^*
- If i is served, revenue from i : $S_i\,(x^*) = \tau(L/M)f(x^*)\beta_i R_i = \tau^*\,\beta_i R_i$
- One can choose convenient units such that $\tau^* = 1$, then revenue from *i* is $\beta_i R_i$
- With limited downlink power it may NOT be possible to serve ALL terminals



Service priorities: Revenue per Hertz

- **It is optimal for the operator to set individual prices such that all terminals choose same SIR x^***
- ***Given bandwidth w, terminal i requires power:*** $P_i^* = \frac{x^* \sigma^2}{w} \frac{R_i}{h_i}$
- ***Power constraint imposes that***

$$\sum P_i = \frac{\sigma^2 x^*}{w} \sum \frac{R_i}{h_i} \le \overline{P} \Rightarrow \sum \frac{R_i}{h_i} \le \frac{\overline{P}/\sigma^2}{x^*} w$$

- ***R_i/h_i tells us "bandwidth consumption" of i . To set priority, look at "revenue per hertz"***
- ***Revenue proportional to $\beta_i R_i$.***
- ***Thus, priority: $\beta_i R_i / (R_i / h_i) = \beta_i h_i$***

Optimal bid

- For the chosen auction, the optimal bid for certain amount of spectrum equals its “yield” (revenue)
- With convenient units, $\beta_i R_i$ is revenue from i (if served).
- To maximize revenue per Hertz, serve terminals in the order of their $\beta_i h_i$.
- *Suppose $\beta_1 h_1 > \beta_2 h_2 >$…etc. Then bid for w has the form*

$$\sum_{i=1}^{I(w)} \beta_i R_i$$

with sum covering all terminals that can be served with bandwidth w

Summary

- We have analysed a simple scenario of market-based DSA in which periodic auctions are used to allocate short term spectrum licenses
- We have focused on the downlink of a single CDMA cell
- The operator must choose jointly a bid and an internal pricing policy
- With convenient units our results acquire simple forms
- We have shown how to determine the:
  - ⇒ optimal QoS for a terminal facing a price per SIR, x*
  - ⇒ price that maximises the operator's revenue
  - ⇒ terminal's "consumption" of bandwidth: R_i/h_i
  - ⇒ Terminal's contribution to revenue (if served): $\beta_i R_i$
  - ⇒ priorities (when not all terminals can be served): $\beta_i h_i$
  - ⇒ optimal bid: $\Sigma\beta_i R_i$

Discussion (1)

- We have considered a simple but rich model: each terminal has its own channel gain, data rate, and “willingness to pay”
- All we know about the physical layer is that the frame-success rate is a nice S-curve; thus many configurations are included!
- We can adjust the link layer for profit maximisation: with L info bits in each M-bit packet, revenues increase with $(L/M)f(x^*)$, but bandwidth usage is proportional to x^*. The link layer with the highest $(L/M)f(x^*)/x^*$ maximises “revenue per Hertz”
- We would prefer that the chip rate of reconfigurable CDMA networks adjust to available bandwidth; but we can handle inflexible chip rates also
- Reference [1] discusses additional functionality needed by DSA
- Cost of upgrade needs to be compared to benefits of DSA

Discussion (2)

- With our results we can analyse DSA among CDMA RAN's. But the greatest gains of DSA come with RANs with different radio access technologies (RAT) having "opposite" "busy hours"
- Ref. [1] reports gains approaching 40% with DSA between UMTS and DVB-T. We will introduce a DVB-T operator in our auctions, and then estimate our "gains" to compare it to those reported
- Our scheme may also serve as an algorithmic metaphor :
  - ⇒ An operator with several RATs could use our scheme to allocate its licensed spectrum internally among its own "divisions": each division may use its "real" budget, or a software agent with a fake budget could play the part of each RAT in internal auctions
  - ⇒ A regulator wanting to dynamically allocate free spectrum could create software agents endowed with fictitious money to play the role of each RAN. No real money would change hands, but the algorithm could still provide a reasonable dynamic allocation