Auction-Driven Dynamic Spectrum Allocation over Space and Time: DVB-T and multi-rate, multi-class CDMA over a 2-island geography

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END-TO-END RECONFIGURABILITY

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UniS

General Philosophy

- The success of 2 recent technologies have revolutionised our ability to exchange and access information:
  - ⇒ the anytime/anywhere connectivity of cellular telephony
  - ⇒ the wealth of information and multimedia capabilities of the Internet
- The Intuitive next step is the marriage of both technologies
- But there are 2 fundamental limitations:
  - ⇒ spectrum (limited by nature) and
  - ⇒ energy (limited by battery and/or power bounds)
- OUR GENERAL APPROACH:

MANAGE SPECTRUM, ENERGY, AND MONEY

JOINTLY !!!

“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 “from scratch”

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, on "pay as you go" basis
- 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)

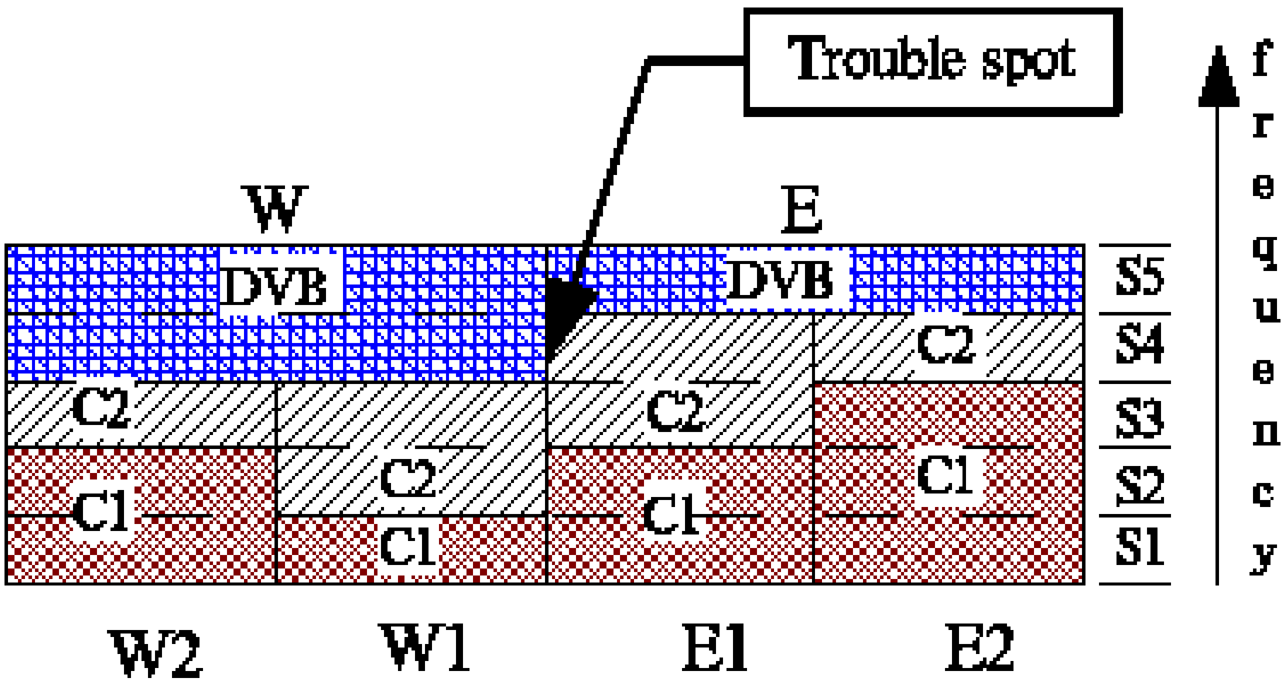
General Idea of this paper

- Our previous work tells us how to do auction-driven DSA:
  - ⇒ on a single “island”
  - ⇒ CDMA networks ONLY (on downlink)
- DSA is most beneficial with the participation of networks that have complementary demand patterns (“loads”)
- UMTS- & DVB-T networks are “load complementary”
- Want to introduce a DVB-T network in our scheme
- A typical DVB cell overlays many UMTS cells (say 20)
- To be “realistic”, need 2 CDMA cells “inside” 1 DVB cell
- Two critical issues:
  - ⇒ “Inter-island” interference control
  - ⇒ DVB needs given frequency band over BOTH or NONE of the islands: Auctions need to consider it.

UMTS interference control

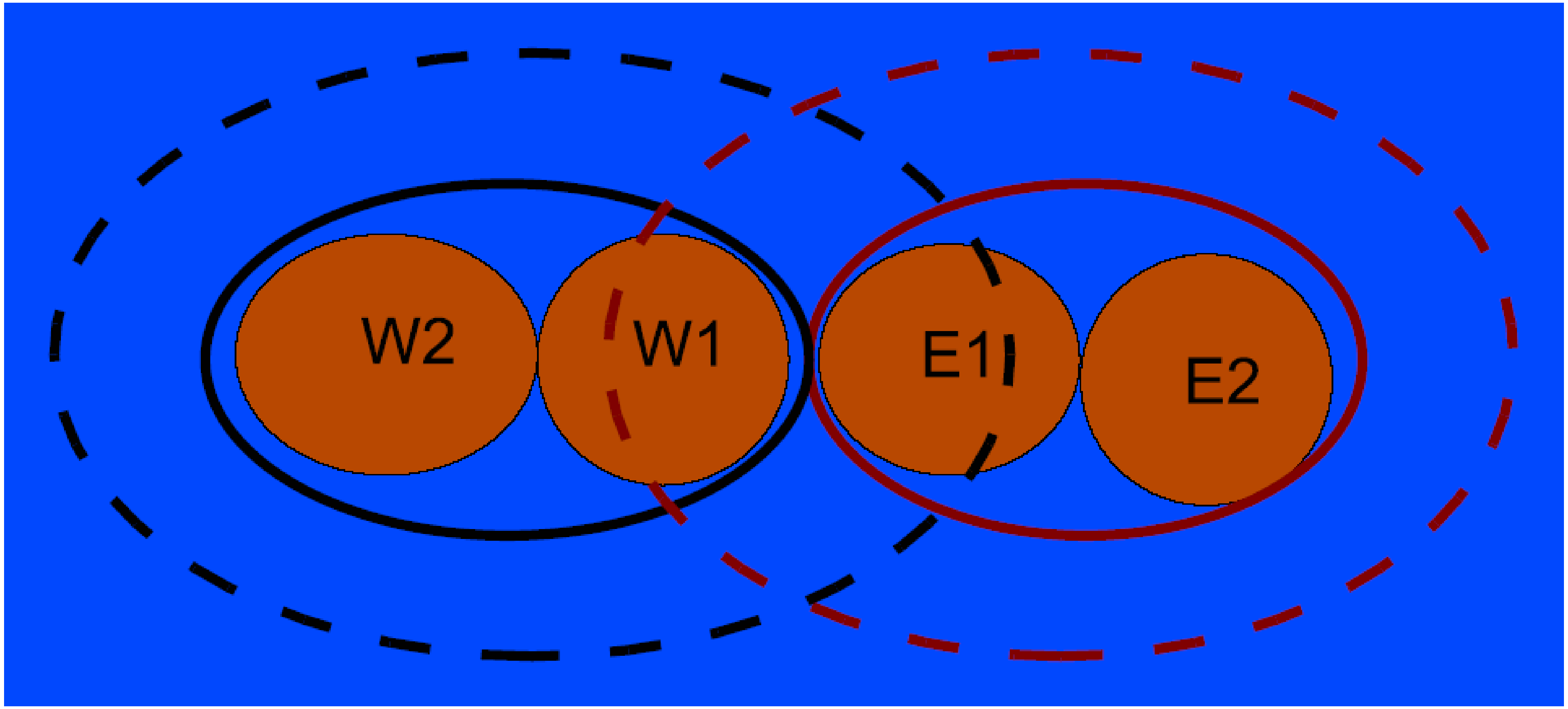
- "Small" islands: Each CDMA network can cover an island with a single cell
- To keep intra and inter island interference under control use UMTS' two layer-spreading
  - ⇒ First, multiply a user's binary data by a "short code", orthogonal to any other such code used in given cell
  - ⇒ Then, already spread sequence is multiplied by a "long code" (such as Gold) unique to a given cell
- On downlink, short codes are assumed to make intra-cell interference negligible. And long codes do same to intercell interference.
- Thus, with 2-layer spreading, downlink CDMA spectrum allocation in one island is independent of other island's.

5 Bands, 4 “islands”, 2 RATs



Problematic allocation of 5 spectrum bands over 4 “islands” (E1, E2, W1, W2). CDMA networks C1 and C2 have one cell per island. 2 large DVB cells (E & W) cover 2 islands each. With 2-layer spreading, the same band can be allocated to different CDMA cells/networks. But a reuse scheme is needed to allocate spectrum to contiguous cells if one of them is DVB.

A 4-island geography



Solid ovals indicate DVB cell. Dashed oval is its “interference region”. We shall initially focus on the west-side only.

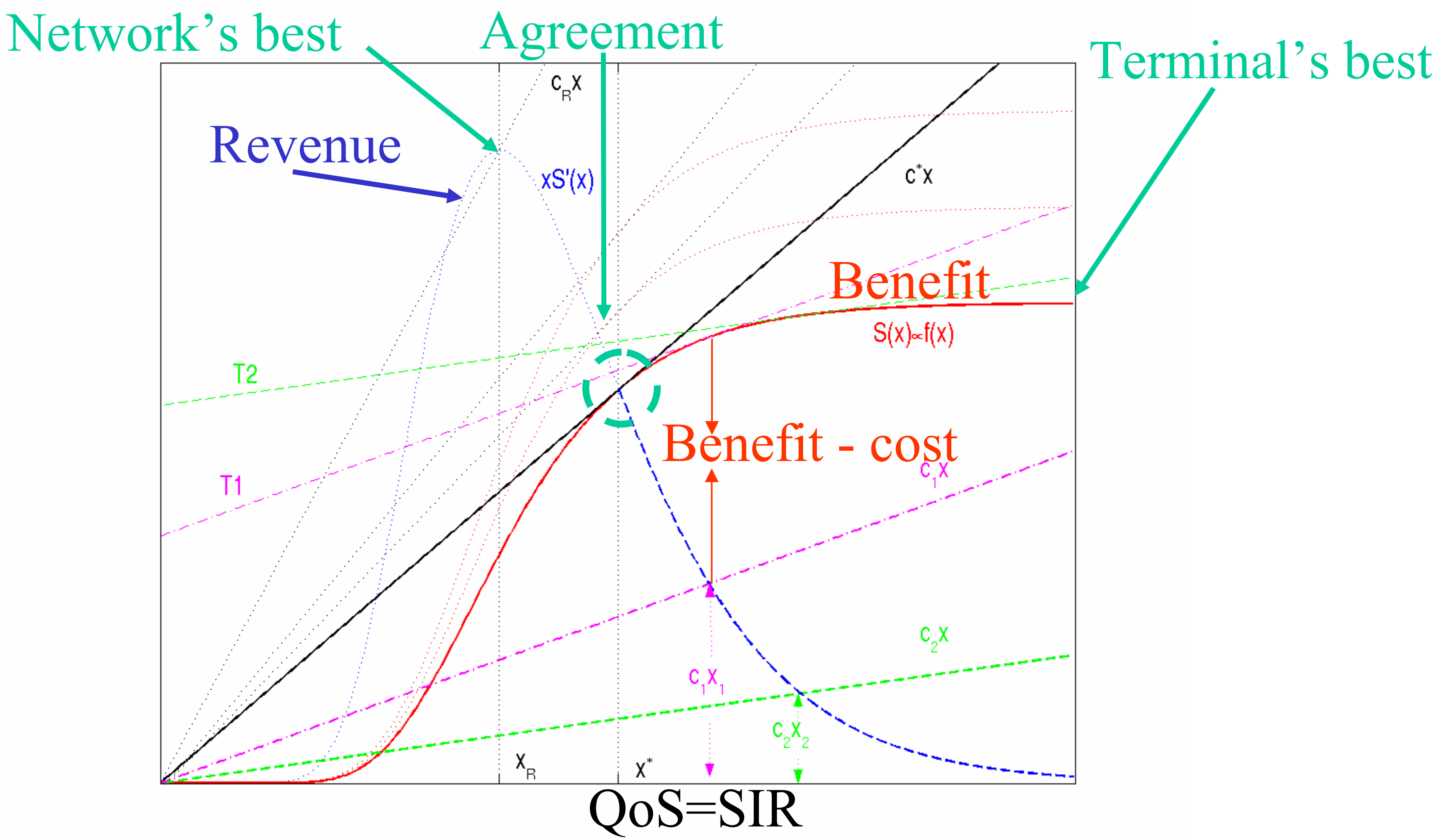
Auction scheme (Vickrey)

- Consider 1 spectrum band only (many bands in paper).
- CDMA networks see independent auctions per island
- All networks simultaneously submit their bids
- By looking first at CDMA bids only, declare ‘interim’ winners per island (highest bidders)
- Now consider the DVB bid: If it exceeds the SUM of the two ‘interim’ winning bids, DVB gets the band, and pays for it this sum
- Otherwise, the ‘interim’ winners are confirmed. Each pays for the band, the highest LOSING bid in its island
- BIDS: It is optimal for each network to submit a bid that equals the revenue it would get from the band

CDMA analysis

- For downlink of a single CDMA cell ("small island")
- Simple but rich model: each terminal has its own channel gain, h_i , data rate, R_i , and "willingness to pay", β_i .
- Network sells to terminal QoS (SIR) at a unit price
- Terminal maximises "utility" = "Benefit" minus cost
- Benefit proportional to throughput and "willingness to pay"
- The network chooses jointly a bid and an internal pricing policy
- With convenient units results are crisp:
- The analysis yields the:
  - ⇒ optimal QoS (SIR) for a terminal facing a price per SIR, x*
  - ⇒ price that maximises the operator's revenue
  - ⇒ more

Opposing interests meet



CDMA results

- terminal's "bandwidth consumption" :

$$R_i/h_i$$

- terminal's contribution to revenue (if served):

$$\beta_i R_i$$

- "revenue per Hertz" priorities (when not all can be served):

$$R_i/h_i \div \beta_i R_i = \beta_i h_i$$

- optimal bid:

$$\Sigma \beta_i R_i$$

with sum covering the (additional) terminals that can be served, if the band is won

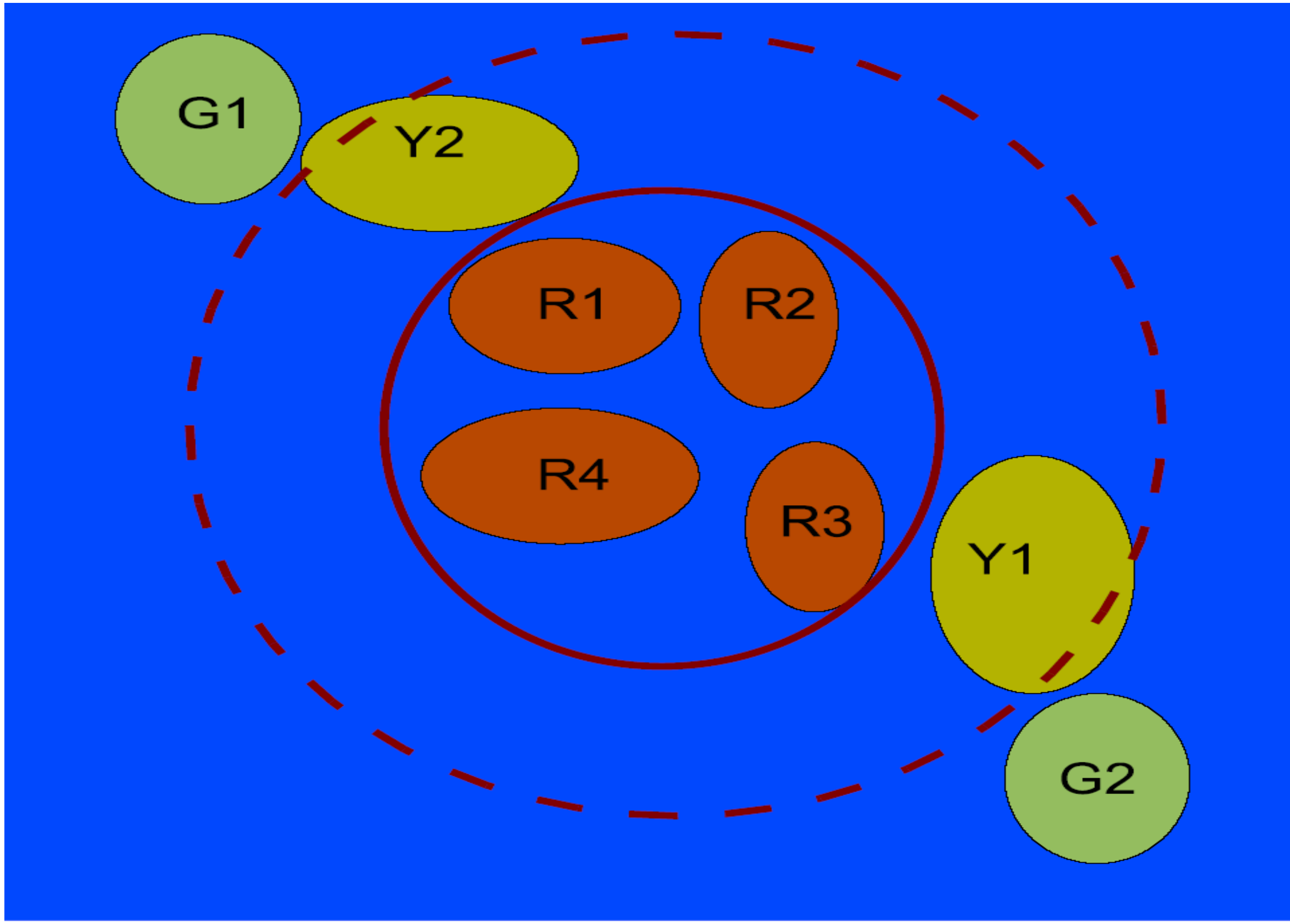
DVB analysis and bids

- Network sells "programmes" (news bulletins, sports updates, entertainment video clips, etc)
- programme has a "value" (customer's willingness to pay)
- Length of programme equals inter-auction period
- Terminals request programmes in inter-auction period
- Several, say m, "programmes" fit in one band
- Network sorts the programmes by the revenue each would bring, and chooses the top m programmes.
- The network's bid is the sum of the revenues that these m programmes would bring, if the band is won

Recapitulation

- To dynamically adjust spectrum allocation as needs change in time and space, we periodically auction 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.
- We consider 2 islands: one DVB-T cell covers both islands, and each of several UMTS-like networks has one cell per island.
- Over CDMA, terminals with dissimilar data rates, channel states, and “willingness to pay” download data. We provide revenue-maximising prices, an optimal operating point, a “revenue per hertz” priority, and a simple bidding strategy.
- Our auction takes into account that a DVB network needs a given band over both islands simultaneously
- We characterise the marketing and bidding behaviour of the DVB cell
- Our results can be extended to more general geographies

Extension to many islands



Solid circle denotes DVB cell, and dashed circle its corresponding “interference region”. To win a band, DVB must beat the sum of CDMA winning bids in red and yellow islands.

Discussion/outlook

- 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
- Future work should address:
  - ⇒ CDMA uplink (interference control more challenging)
  - ⇒ Contiguous DVB cells (frequency reuse issues)
  - ⇒ Other radio-access technologies

DSA over space and time with 2 access technologies