Market-Driven Dynamic Spectrum Allocation

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END-TO-END RECONFIGURABILITY

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.

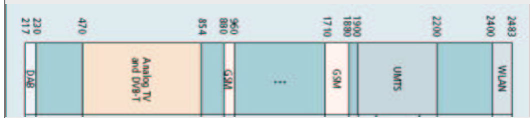
❖Current spectrum licensees can adopt our scheme under a "resource pooling" business model, involving an intermediary.

❖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.

❖We have analysed a scenario where 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.

0. Background: Problems of traditional allocation



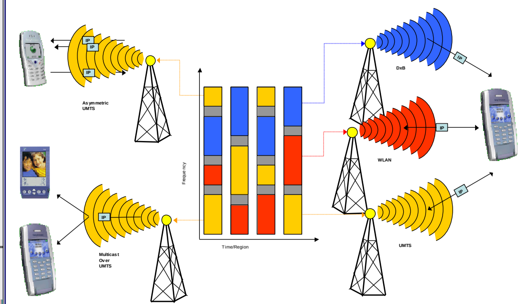
❖ **How is it done?**

- Available spectrum is split in bands allocated to specific radio-access technologies (RAT) (DVB-T, UMTS, etc)
- Some bands are left "open" (e.g. WLAN), but most are further divided and allocated for exclusive use for a "long" time
- License transfer/trading is highly restricted, in general
- Spectrum given to a RAT typically can**not** be used for another

❖ **What is wrong with it?**

- Networks are designed for "busy hour". Region with largest projected demand determines allocation for entire network
- At specific time and place, a RAT may be in very high demand, while another is lightly loaded. In fact, some RAT's consistently have opposite "busy hours".
- Even networks on the same RAT may face dissimilar "loads":
  - ➢The market share of a network may not match its original spectrum allocation (long term forecast may be wrong), and market share may vary from a place to another, and from a time to another, while spectrum shares remain fixed
  - ➢Random events can make a network considerably busier than others at specific instants
- License trading could remedy some of the long term imbalances, but not the short term ones.

Dynamic spectrum allocation in action



Thanks to IST overDRiVE project

1. Our approach: "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 entire process is re-initiated again

2. Ours versus 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	No, Voice-only UMTS
Video Services	DVB & CDMA (future)	Only on DVB-T
Physical layer; Resource management	Considered (data rates, power, channel gains). General channel model	Not considered (e.g., a UMTS band always holds a fixed # of calls)
Value/importance of service to user	Considered	Not considered
Methodology	Analytical/simulation	Simulation only

3. Plausible business model

❖Licensees create and keep a spectrum management firm, and transfer their current licenses to this new firm

❖Firm utilizes some agreed-upon economic mechanism (auction) to allocate short-term spectrum licenses to the participating operators (and anyone else they approve)

❖The firm's profits are eventually shared among the owners (the original spectrum licensees)

❖State could monitor arrangement for antitrust purposes

4. Key Issues

❖ "Guiding principle" of spectrum manager: If managing firm is owned by the original spectrum licensees, profit maximisation seems reasonable (makes possible new entrants). If state agency is the manager, efficiency/fairness issues seem more important. Our scheme works either way

❖ How to allocate licenses:

- ❖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 frequently (minutes?) they must be "direct". A computerised procedure implementing a "sealed bid" auction is envisioned.
- ❖Counter-measures to "malicious" behaviour to be imposed as appropriate for chosen auction format
- ❖We have studied the Vickrey (2nd price) auction

❖How fast licenses expire determined mostly by technology: the sooner the better, but network reconfiguration is challenging

5. Vickrey spectrum allocation process

❖ Divide the available spectrum into K (say 3) "bands"

❖Assume bands are identical for considered technologies

❖A bid is a K-dimensional 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 be assigned to same bidder.

❖Payment: a winner of k bands pays the sum of the k highest LOSING bids submitted by others

❖It is well known that in this auction the optimal bid equals the "value" (revenue) of a (an additional) band to the bidder

6. Our Results

❖We have solved the problem of the operator of the downlink of a single CDMA cell. The operator must choose jointly a bid and an internal pricing policy for its customers.

❖Let β_i, R_i and h_i be respectively a terminals "willingness to pay", data rate and channel gain. With convenient units our results acquire simple forms. We have learned how to determine the:

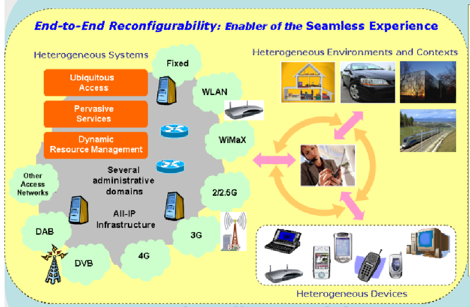
- quality-of-service level where the interests of the terminals and operator meet, a value determined by the physical layer
- price that maximises the operator's revenue
- terminal's "consumption" of bandwidth: R_i/h_i
- terminal's contribution to revenue (if served): $\beta_i R_i$
- "revenue per Hertz priorities (when not all terminals can be served): $\beta_i h_i$
- optimal bid for one band: $\Sigma\beta_i R_i$ (sum covers the (additional) terminals that can be served if the band is won)

Key References

[1] Rodriguez, V., et al., "*Market-driven dynamic spectrum allocation: Optimal end-user pricing and admission control for CDMA*", to appear, IST Summit, June 2005

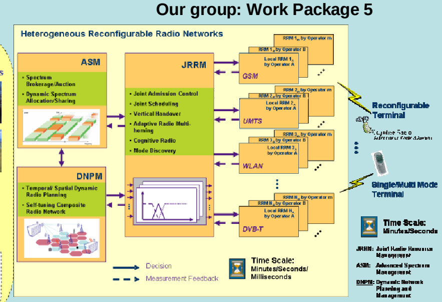
[2] Leaves, P., et al., "*Dynamic spectrum allocation in composite reconfigurable wireless networks*" *IEEE Communications Magazine*, v. 42, 2004

Our project: End-to-End Reconfigurability



http://e2r.motlabs.com

Our group: Work Package 5



Group Objectives:

To define, develop and initially assess:

- new and innovative system engineering mechanisms with the aim to facilitate more efficient spectrum use in a multi-radio networks environment.
- the performance of concepts of reconfigurable architecture models that enabling the application of new RRM and SM system functions and strategies in multi-radio networks environments.
- To specify the basic principles, define schemes and analyse dynamic network planning and management (DNPM) in the multi-radio environment.

Additional Details

Vickrey auction: a numerical example

Suppose 3 bands are available and only bids B1=(5,3,2) and B2=(4.5,4,1) are submitted

❖**Allocation:**

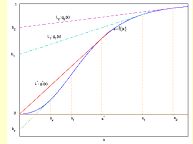
- **One band to bidder 1 (5 is top bid)**
- **Next band to bidder 2 (4.5 is second-highest bid)**
- **Last band also to bidder 2 (4 is next highest bid)**

❖**Payments:**

- **Bidder 1 got 1 band, and must pay highest LOSING bid from bidder 2 : 1**
- **Bidder 2 must pay sum of 2 highest LOSING bids from bidder 1 : 3+2=5**

The Physical Layer

- **Terminal's performance depends on physical layer (modulation, FEC, diversity, etc)**
- **Frame-success rate function f(x) (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**
- **We assume all we know about f(x) is its S-shape**
- **On downlink, intra-cell interference can be neglected or included with noise term (σ^2)**
- **SIR: $x=GQ/\sigma^2$; G=bandwidth/data_rate, Q=hP ; P: power, h: channel gain**



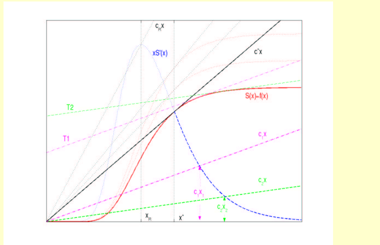
$$f(x) = \left[1 - \frac{1}{2}\exp\left(-\frac{x}{2}\right)\right]^{80}$$

CDMA operator's problem

- ❖ Given a set of "users" 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
- ❖ And 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 uses pricing to generate revenue AND to encourage efficient resource usage
- ❖ Terminal charged per Watt of allocated power

Terminal's behaviour

- ❖ Given pricing structure (linear), terminal must choose power to maximize "utility".
- ❖ For downlink, assume utility of the form $\beta_i B_i + y_i$
  - o B_i: # of bits correctly transferred in reference period, τ
  - o β_i: monetary "value" to terminal of 1 correct bit
  - o 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
  - o R_i is the data rate, *x* is received SIR
  - o *f(x)* is frame-success rate
- ❖ Terminal **converts price per Watt to price per SIR (x) and** order power to make *x* maximise *S(x)-cx* where S is an S-curve (because B_i is proportional to f(x))



Terminal's choice

❖**Terminal converts price per Watt to price per SIR (x)**

❖**if cx > S(x) for all 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 $c_1 x$)**

❖**operator's revenue is then $c_1 x_1 = x_1 {}^* S'(x_1)$**

Operator's choice

❖For $c_1 < c^*$ terminal chooses x_1 such that $c_1 x_1 = x_1 S'(x_1)$

❖the curve xS'(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 $S(x^*) = \tau(L/M) f(x^*) \beta R \propto \beta R$

❖ With many terminal, 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^*.

"Revenue per Hertz" priorities

❖It is optimal for the operator to set individual prices such that all terminals choose same SIR x^*

❖*Terminal i requires power:* $P_i^* = \frac{x^* \sigma^2}{w} \frac{R_i}{h_i}$

❖*Power constraint:*

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

❖*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 at the optimal SIR with bandwidth w

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