Simple decentralised market-oriented management of OFDMA Femto-cells

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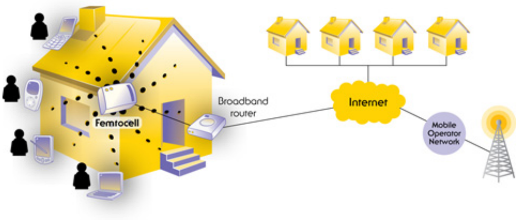
Executive Overview

- Femto access points (FAP) are “do it yourself” home “base stations” attached to a “normal” cell of a cellular network
- They can improve indoor coverage, and increase capacity, for little money (partially absorbed by end-user)
- But they greatly complicate resource allocation and reuse
- OFDMA femto-cells are especially important: 4G networks!
- Challenge: to efficiently allocate channels (with spatial reuse) and power to coexisting macro and femto users
- For the down-link, we auction sub-channels and price macro-users power, and utilise post-winning “confirmation messages” to reuse channels spatially within the cell
- Our scheme can involve real money (service fees), or be implemented as a decentralised low-complexity algorithm

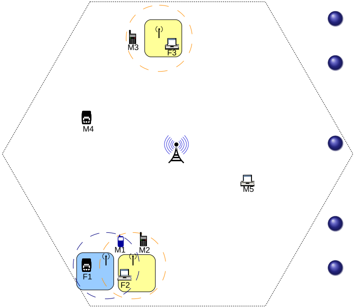
Femto-cells: what, why, why not?



Thanks to femtoforum.org

- femto access point (FAP): low-cost, low-power device suitable for home owner installation
- creates tiny cell (femto:10^{-15}) under a “macro” cell to:
  - improve user experience in indoor locations
  - increase system capacity for a modest investment partially provided by end-users
- But their unplanned, dynamic nature greatly complicates
  - resource allocation and reuse
  - interference control.

Femto-cells resource challenges (down-link)



- M1 to M5 are attached to macro-cell
- F1 to F3 are attached to a respective FAP
- FAP-1 can interfere with F2, but FAP-2 does not interfere with F1
- A channel assigned to FC1 or FC2 could be reused at FC3
- FAP-1 & FAP-2 can each interfere M1
- Only FAP-2 & only FAP-3 could interfere with, respectively, M2 & M3
- NO FAP interferes with either M4 or M5

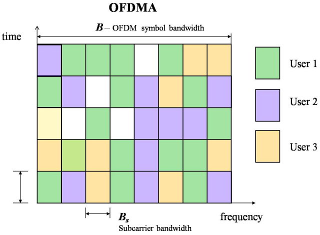
The free market as a paradigm for algorithms

- A complex technological system can be “efficiently” managed 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

Auctions for short-term allocations: Why?

- To quickly allocate resources to those that most value them
- A terminal's valuation of a resource could either
  - represent the "true" "willingness to pay" of a user, or
  - be a "priority" index computed/adjusted by software
- The Dutch auction format is of interest:
  - Public "clock" displays a progressively falling price
  - Eventually bidder that most values object "takes it"

OFDMA management: Basic issues



- OFDMA down-link cell with K terminals
- Bandwidth split into N sub-carriers
- Resources assigned once per time-slot
- Channel-state info at BS enables:
  - Dynamic sub-carrier assignment (NP-hard!!)
  - Adaptive power allocation ("water filling")
  - Adaptive modulation and coding
- Allocate "sub-channels" (several sub-carriers) to reduce overhead

Market-based OFDMA management

- Just before the time-slot of interest, network auctions the sub-carriers in parallel through a Dutch auction
- When the price for a given sub-carrier is low enough, the terminal that “most values” it sends a buy signal
- This terminal also optimally buys down-link power, given a price set by network
- After purchase completed, prices resume dropping, until another purchase occurs

Algorithmic view

CalculateInitialBids
FindTopBid |{ Find overall highest bid

$price \leftarrow priceMax$ |{ Initial high price

while $price \geq 0$
do $\begin{cases} \textbf{if } TopBid \geq price \\ \quad \textbf{then } \begin{cases} AssignChannel \\ UpdatePowerBudget \\ UpdateBids \\ UpdateTopBid \end{cases} \\ price \leftarrow price - \Delta \end{cases}$ |{ Decrement price

Initial bid calculations

- A terminal's bid determined by its "valuation" of a channel
- Valuation: Benefit minus associated cost
- "Benefit": "value" of the (additional) information that the terminal can transfer if it wins the channel
- With 1 sub-carrier/channel, & delay-tolerant traffic, if term i has NOT yet won, it values ch n as $\beta_i R_{i,n}(p^*_{i,n}) - c_i p^*_{i,n}$:
  - β_i: monetary value of 1 info bit multiplied by SC bandwidth
  - $R_{i,n}(p) = \log_2(1 + ph_{i,n})$
    (bits/Hertz with power p & normalised channel-gain $h_{i,n}$)
  - $p^*_{i,n} = \min(p_{i,n}, P)$ with P the remaining power, c_i the price & $p_{i,n}$ solves single-variable equation $R'_{i,n}(p) = c_i/\beta_i$.

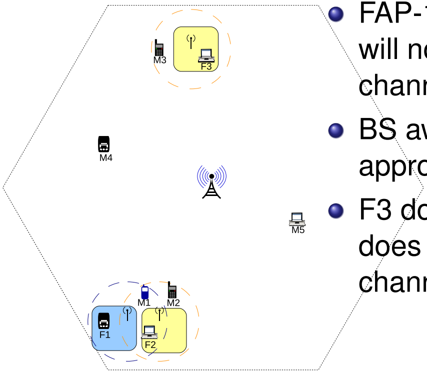
Introducing OFDMA Femto-cells (down-link)

- Assume that each FC has at most 1 active terminal (real FAP can handle only a few active terminals)
- Power price only for macro-terminals
- FAP efficiently allocates its total power to all channels won by its only terminal (e.g., "water-filling")
- If a FC terminal sends a buy signal,
  - FAP sends an approval message, over both the FAP-BS link, and the air (for interference control)
  - After receiving the approval, the buying FC terminal sends a short confirmation, also for interference control.
- If a macro-terminal wants to buy, all work as before, but BS will not approve if channel is already assigned to a FC

Channel reuse and interference control

- Too much interference at FC if it shares channel with MC
- NO macro <–> femto interference because:
  - BS and each FAP inform each other of channel approvals
  - BS will NOT approve a MC bid for a FC-won channel
  - FAP will NOT approve a buy attempt of a MC-won channel
- Approval/confirmation messages allow FC channel reuse without interference under symmetric channels:
  - if a FC terminal can "hear" a FAP, they can hear each other
  - If FAP hears a "foreign" confirmation, it will NOT approve a future buy attempt (by its own terminal) of that channel
  - If FC terminal hears approval by "foreign" FAP, it will NOT bid for that channel (to avoid interference by that FAP)
- NO problem (on down-link) if
  - FAP "hears" foreign FAP but NOT "foreign" terminal, or
  - terminal "hears" a "foreign" terminal, but not the foreign FAP

Channel reuse and interference control example



Suppose F2 confirms a channel purchase

- FAP-1 does hear F2's confirmation and will not approve an F1 buy attempt for this channel (& F1 will never confirm it)
- BS aware (via BS-FAP link), & will not approve a MC buy attempt of this channel
- F3 does not hear the FAP-2 approval, nor does FAP-3 hear F2's confirmation; channel remains available at FC3

Valuation by femto-cell data terminal

- FC terminal has no power cost (uses zero BS power)
- Its valuation equals the value of the (additional) information it can transfer over the channel
- If it has a "long" queue of data, and has not yet won a channel, its valuation is $\beta_i R_{i,n}(p)$
  with β_i & $R_{i,n}(p) = \log_2(1 + ph_{i,n})$ as before
- With only 1 active terminal per FC, p is the total FAP power
- If it has already won channels in this auction, bid calculation is slightly more complicated ("water-filling")

Implementation: issues & non-issues

- Auction parameters should be optimised, considering
  - statistics of the “valuations” (to set max price, and “step”)
  - signal processing/travel times (clock tick long enough for bidding/confirmation messages)
- Possible “non-problems”:
  - All participants must be tightly synchronised, but this is already required in 4G nets
  - FAP-BS link must be fast enough for operations discussed (home Internet: 10-100 Mbps now + steady improvement)
  - Simultaneous bids are highly unlikely because they depend on continuous random variable (channel gains)
  - 4G standards are dynamic; future new features may facilitate implementation

Recapitulation

- Decentralised sub-channel/power allocation scheme for the OFDMA down-link with femto-cells
- Keys: simple descending-price channel auctions, with a price for base-station power use and confirmation messages for femto-cells channel reuse
- Channel reuse key: FAP focuses on "foreign" confirmations, FC terminal on "foreign" FAP approvals
- Key computation done by terminal: how much to bid?; more complex after previous wins ("water-filling")
- Low complexity: global NP-hard channel/spatial-reuse power allocation avoided
- Tendency: channel goes to terminal that can transfer the "highest value"of information through it
- Bids can be "true" service fees (money), or "priorities"
- "Best effort" apps assumed (e-mail, web browsing, etc). Fix-rate user must bid "high enough" to win what it needs.
- Work is conceptual/analytic. Simulation anticipated.

Bid re-calculation after a previous winning

- For i to evaluate SC n after it has won m, it solves:

$$\max_{x,y} \beta_i(R_{i,m}(x) + R_{i,n}(y)) - c_i(x+y) \quad \text{s.t. } x+y \leq P$$

- If x^*, y^* are the optimisers, the terminal only needs $x^* + y^* - p^*_{i,m}$ because it bought $p^*_{i,m}$ when it won SC m.
- The increase in benefit brought by sub-channel n is:

$$\beta_i(R_{i,m}(x^*) + R_{i,n}(y^*) - R_{i,m}(p^*_{i,m}))$$

(benefit with both m and n minus benefit if only$m$)

- $\therefore$ $i's$ valuation of SC n after it has won m is:

$$\beta_i(R_{i,m}(x^*) + R_{i,n}(y^*) - R_{i,m}(p^*_{i,m})) - c_i(x^* + y^* - p^*_{i,m}) \equiv$$
$$[\beta_i(R_{i,m}(x^*) + R_{i,n}(y^*)) - c_i(x^* + y^*)] - [\beta_i R_{i,m}(p^*_{i,m}) - c_i p^*_{i,m}]$$

Valuation after several winnings

- A terminal that has won $M-1$ bands and evaluates an additional one must solve a problem of the form:

$$\max_{x_1,\cdots,x_M} \beta_i \sum_{m=1}^{M} R_{i,m}(p_m) - c_i \sum_{m=1}^{M} p_m$$
$$\text{s.t.} \sum_{m=1}^{M} p_m \leq P \qquad (1)$$
$$p_m \geq 0$$

- The solution (provided separately), has the “water-filling” form: $p_m + 1/h_m = 1/(c+\lambda)$

Extension: Macro/Femto channel sharing (down-link)

- For any terminal, any approval –> channel taken
- Approvals:
  - FAP uses max power
  - BS uses power ordered by winning terminal
- Confirmations:
  - FC-terminal sends TWO consecutively,
    - 1st uses max BS power
    - 2nd uses max FAP power
  - Macro terminal sends TWO, each at max FAP power
- Interpretation of confirmations:
  - For BS, one confirmation –> channel taken
  - For FAP, 2 consecutive confirmations –> channel taken

MC/FC channel reuse and interference control

- NO femto-to-femto interference for the same reasons already given under previous scheme
- NO BS to femto interference because:
  - If FC terminal can "hear" the BS, the BS can also "hear"1st confirmation from that FC (sent using max BS power)
  - BS will NOT approve a MC bid for a FC-won channel
- NO FAP to macro-cell interference because:
  - If macro-terminal can "hear" a FAP, this FAP can also "hear" the confirmations sent by that MC terminal
  - FAP will NOT approve a buy attempt for a channel over which the FAP has "heard" a MC-confirmation