Simple decentralised market-oriented allocation of sub-channels and power for access-point to terminal multi-carrier communication

Virgilio RODRIGUEZ[1], Rudolf MATHAR

Theoretische Informationstechnik
RWTH Aachen
Aachen, Germany
email: vr@ieee.org

18 March 2010

[1] Supported by the DFG UMIC project

Executive Overview

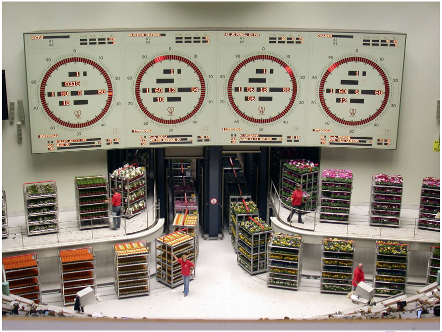
- Orthogonal frequency-division multiple-access (OFDMA) is the technology of fourth generation (4G) cellular networks
- Efficient resource allocation is critical to 4G success
- Main issues are allocating sub-channels and power levels to individual terminals
- A decentralised solution is preferable because of the high complexity of finding the globally optimal allocation
- For the base-station-to-mobile link, we combine auctions — to allocate the sub-channels — with per-Watt pricing
- Our scheme can involve real money (service fees), or be implemented as a decentralised low-complexity algorithm
- We now discuss conceptual/qualitative/analytical issues. Numerical studies focused on 4G networks are anticipated

The free market as a paradigm for algorithms

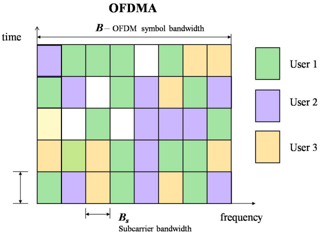
- A complex technological system can be “efficiently” managed as an “economy”
- The system can be viewed as integrated by many “agents”
- Agents may correspond to actual human beings, or may be machines, or processes
- The system administrator sets up some relatively simple rules for resource use and 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 downlink 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

Economorphic OFDMA management

- Semi-decentralised market oriented (economic) approach
- Basic idea:
  - Just before the time-slot of interest, network auctions the sub-carriers in parallel by means of a descending-price "clock" auction (Dutch auction)
  - When the price for a given sub-carrier is low enough, the terminal that "most values" it sends a buying signal.
  - This terminal also purchases its optimal amount of down-link power for that sub-carrier, given a per-Watt price set by the network
  - After a given sub-carrier is won, the price of each of the others continue to drop until a terminal buys it.

Initial bid calculations

- A terminal's bid closely related to its "valuation" of a SC
- Valuation: Benefit minus associated cost
- "Benefit": "value" of the (additional) information that the terminal can transfer if it wins that SC
- Assuming one sub-carrier per sub-channel, a data (delay tolerant) terminal that has NOT yet won anything, values SC n as $\beta_i R_{i,n}(p^*_{i,n}) - c_i p^*_{i,n}$ where :
  - β_i is the monetary value of one information bit successfully transferred multiplied by the SC bandwidth
  - $R_{i,n}(p) = \log_2(1 + ph_{i,n})$ (information bits/Hertz terminal can transfer over SC n with power p and channel-gain over noise equal to $h_{i,n}$)
  - For price c_i, $p_{i,n}$ is the solution to single-variable equation $R'_{i,n}(p) = c_i/\beta_i$ and $p^*_{i,n} = \min(p_{i,n}, P)$ where P is the remaining power.

Bid re-calculation after a previous winning

- If terminal i wants to evaluate SC n after it has won SC m it must solve:

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

- 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:

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

(the benefit from having both m and n minus that of having m alone).

- Thus, the valuation of SC n after m has been won is:

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

Valuation after several winnings

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

$$
\begin{aligned}
\max_{x_1,\cdots,x_M} \beta_i \sum_{m=1}^{M} R_{i,m}(p_m) - c_i \sum_{m=1}^{M} p_m \\
\text{s.t.} \sum_{m=1}^{M} p_m \le P \\
p_m \ge 0
\end{aligned} \tag{1}
$$

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

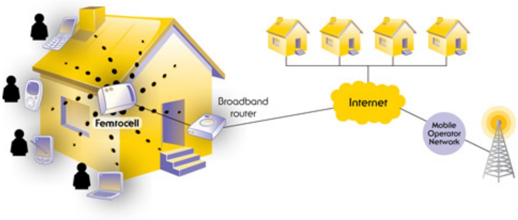
Implementation issues

- Auction requires tight synchronisation among terminals, i.e., a “common clock” (NOT a problem for 4G networks)
- Auction parameters (initial price, the clock “tick”, and price “step”) should be chosen judiciously, considering statistics of the terminals’ “valuations”, and signal processing/travel times, among other factors
- Simultaneous bids are in principle possible. However, if channel gains are continuous random variables, so are valuations and bids; therefore, the probability of tied bids is negligible.
- Can this scheme be implemented within the constraints imposed by present 4G standards?

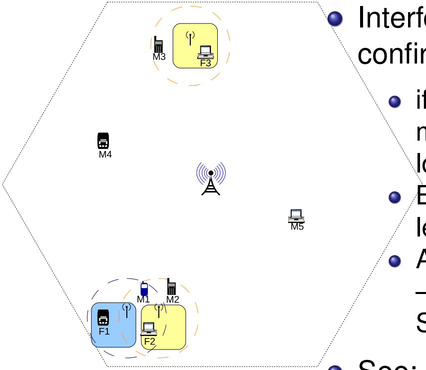
Summary

- Decentralised sub-channel/power allocation scheme for the forward-link of an OFDMA cell.
- Based on simple descending-price auctions, one for each sub-channel, run in parallel at each time slot
- Scheme is low complexity: global NP-hard sub-channel/power allocation problem avoided.
- Key computation done by each terminal in calculating its bid in a “channel by channel” basis.
- Bid calculation become more complex, as a given terminal wins more sub-channels
- Tendency: sub-channel goes to terminal that can transfer the “highest value”of information through it
- Auction can involve real money (service fees), or the bids may represent “priority” indeces
- Data traffic (“best effort”) (e-mail, web browsing, etc) has been assumed. If a terminal requires minimum data rate, it must bid “high enough” to always win necessary resources
- So far work is conceptual/analytic. Simulation anticipated.

Extension: OFDMA Femtocells



- femto access point (FAP): low-cost, low-power device suitable for home-owner installation
- operates underneath a standard cell, in licensed spectrum bands and can
  - improve user experience in indoor locations,
  - increase overall system capacity
  - with modest monetary investment.
- But the unplanned dynamic nature of these cells, significantly complicates resource allocation and interference control.



- Our scheme can be adapted to femtocells
- Interference controlled through confirmation messages, e.g.,
  - if M1 or M2 hear FAP-2 confirm a buy message, M1 and M2 infers the SCI is no longer available
  - BS confirms over the air confirmation, leaving available BS power unchanged .
  - Any FC terminal that did not hear FAP-2 — e.g., FAP-3 — will continue to treat the SC as available
- See: IWCMC starting June'10, in France