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

Virgilio RODRIGUEZ, Rudolf MATHAR

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

18 March 2010

1Supported by the DFG UMIC project
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:
  - $\beta_i$ 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:

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

- 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:

$$\beta_i(R_{i,m}(x) + R_{i,n}(y) - R_{i,m}(p_{i,m}^*)) - c_i(x + y - p_{i,m}^*) \equiv \left[ \beta_i(R_{i,m}(x) + R_{i,n}(y)) - c_i(x + y) \right] - \left[ R_{i,m}(p_{i,m}^*) - c_i p_{i,m}^* \right]$$
Valuation after several winnings

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

$$
\max_{x_1, \ldots, x_M} \beta_i \sum_{m=1}^{M} R_{i,m}(p_m) - c_i \sum_{m=1}^{M} p_m
$$

subject to:

$$
\sum_{m=1}^{M} p_m \leq P \quad (1)
$$

$$
p_m \geq 0
$$

- 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?
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” indices.

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.
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