Flexible and heterogeneous: Radio access beyond 3G

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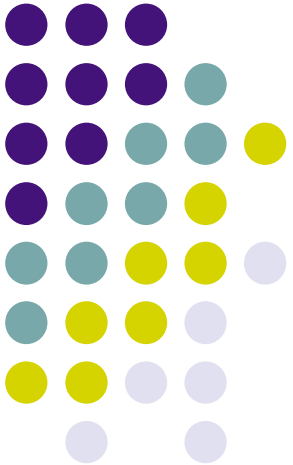
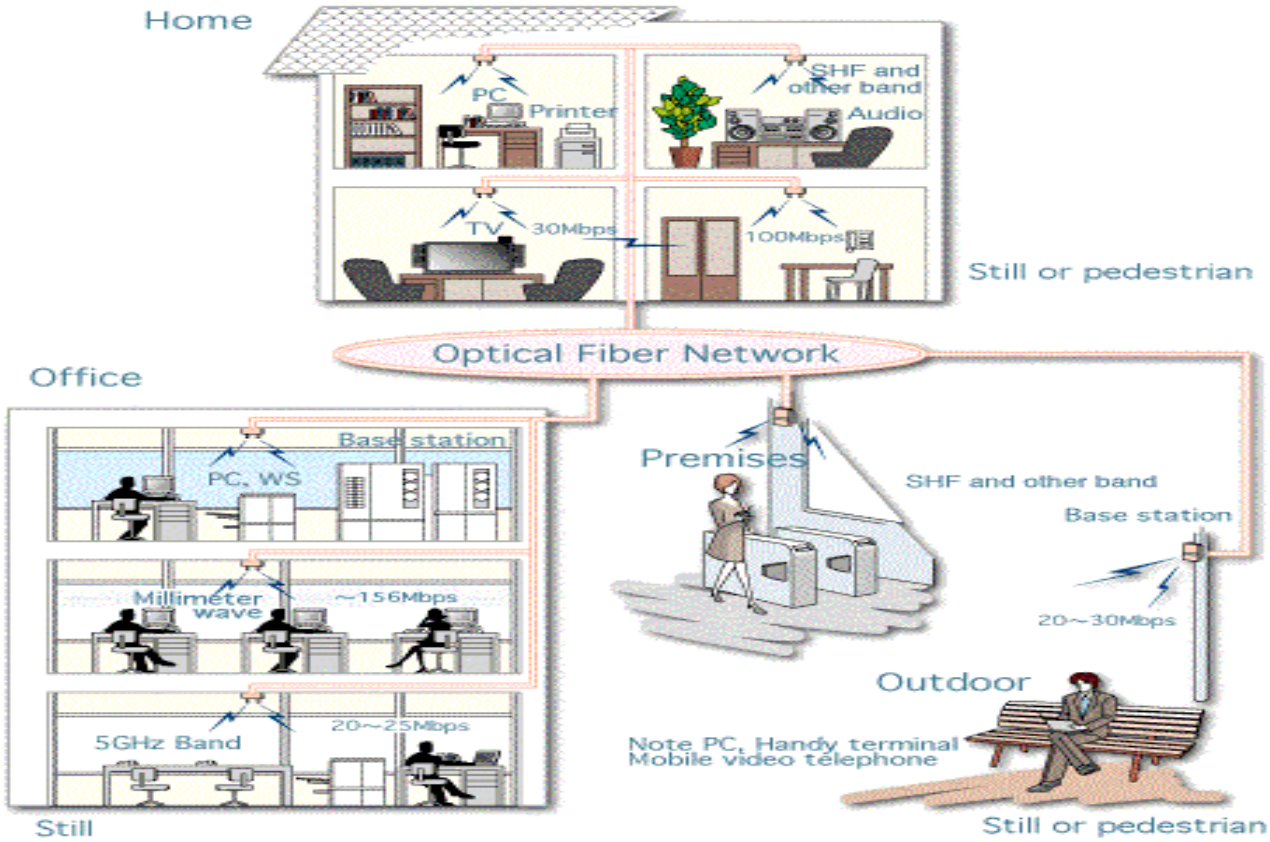
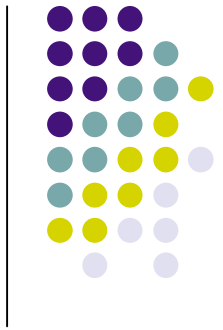


Two major goals

- Broadband for All
- Access Everywhere

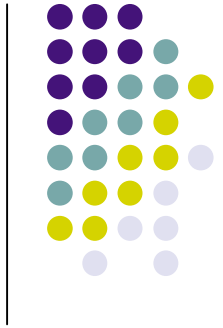


Some major trends



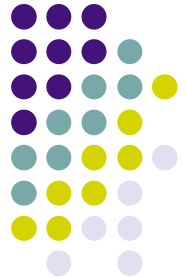
- Shift towards bursty, high-speed multimedia (e.g. streaming video) data traffic; IP-based (wireless Internet) => *Demand for high spectral efficiency.*
- Increased demand for *mobility* (higher speeds + wider range).
- Seamless, ubiquituous wireless (and wired) access across *heterogenous networks*; multi-layered *ad-hoc* network structures
- *Cooperation* across terminals and sub-networks (e.g. multi-hop relaying).
- *Reconfigurability, adaptivity, programmability, flexibility* - of terminals, access schemes, and services.

Some major trends, cont'd



- Regulatory reforms: Use of *new (higher) frequency bands*, release of BW previously used for analogue broadcasting, etc.
- Shift from wide-range to *short-range* radio communications (nano- and picocells, WLANs, PANs, multi-hop).
- Integration of *sensors* into communication networks.
- Ever-increased *processing power and memory* available in terminals.
- More and more battery-driven devices - *energy efficiency* essential (battery technology still limited).

4G - What is it?

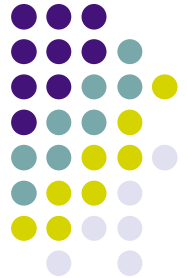


- 4G = 4th Generation mobile communications
- 4G = B3G = Beyond 3rd Generation (UMTS, IMT-2000) mobile communications
- Foreseen to become available *after 2010*.
- ITU Recommendation ITU-R M.1645:

  Systems beyond IMT-2000 will be realized by functional fusion of existing, enhanced, and newly developed elements of IMT-2000, nomadic wireless access systems and other wireless systems, with high commonality and seamless interworking.

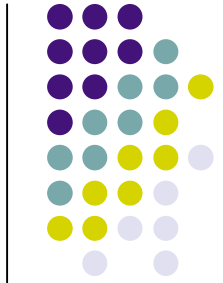
- I.e., a *mix of many interacting systems* is foreseen - not one standard.
- Targeted data rates (with wide area coverage and significant mobility) are in the area of *50 to 100 Mbits/s*.

What are the most promising radio technologies for B3G systems?



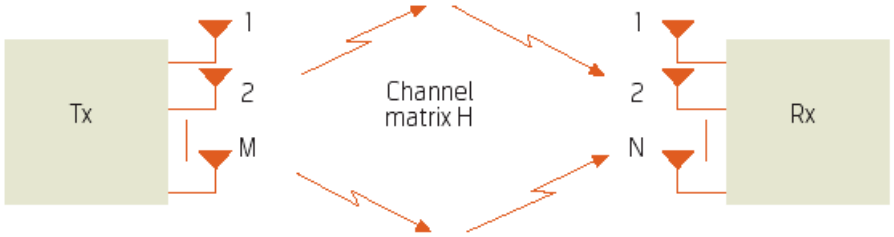
- MIMO (Multiple-Input Multiple Output) technology
- Link adaptation techniques
- Multi-carrier based modulation and access
- Iterative (multi-user) processing
- ”Cross-layer” optimization and design principles
- W-CDMA...? [UMTS solution]
- Ultra-WideBand (UWB)...?

MIMO technology



- May be the single most important technology component for enhancing capacity, link reliability, and coverage in wireless systems [Foschini & Gans 98]
- Employs *multiple transmit and receive antennas*, to exploit channel fading effects constructively, and achieve different kinds of gains:
  - Spatial diversity gain (combat fading, stabilize link quality, increase coverage and QoS)
  - Spatial multiplexing gain (transmit multiple independent data streams, increase link capacity)
  - Array gain (capture more received energy, improve average SNR, increase coverage and QoS)
  - Co-channel interference reduction gain (attenuate interference from adjacent cells, increase cellular capacity)

MIMO technology, cont'd



An MxN MIMO system.

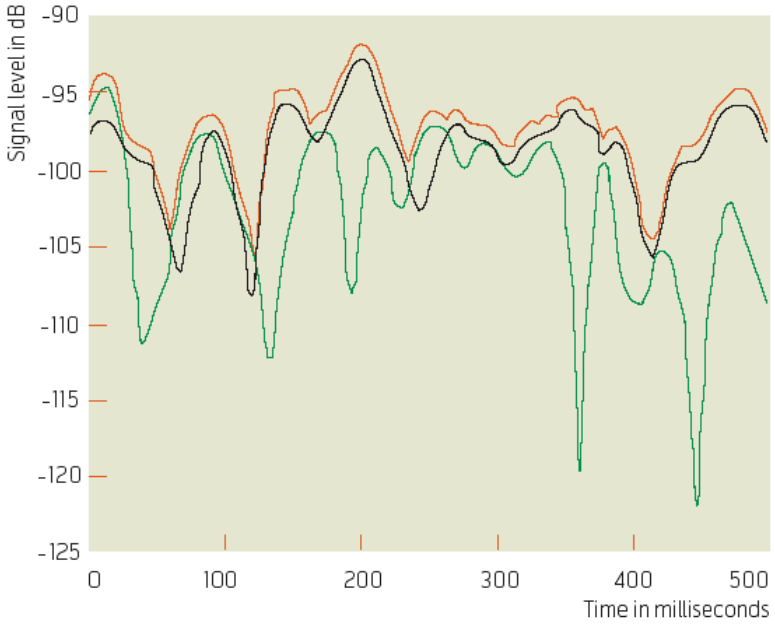
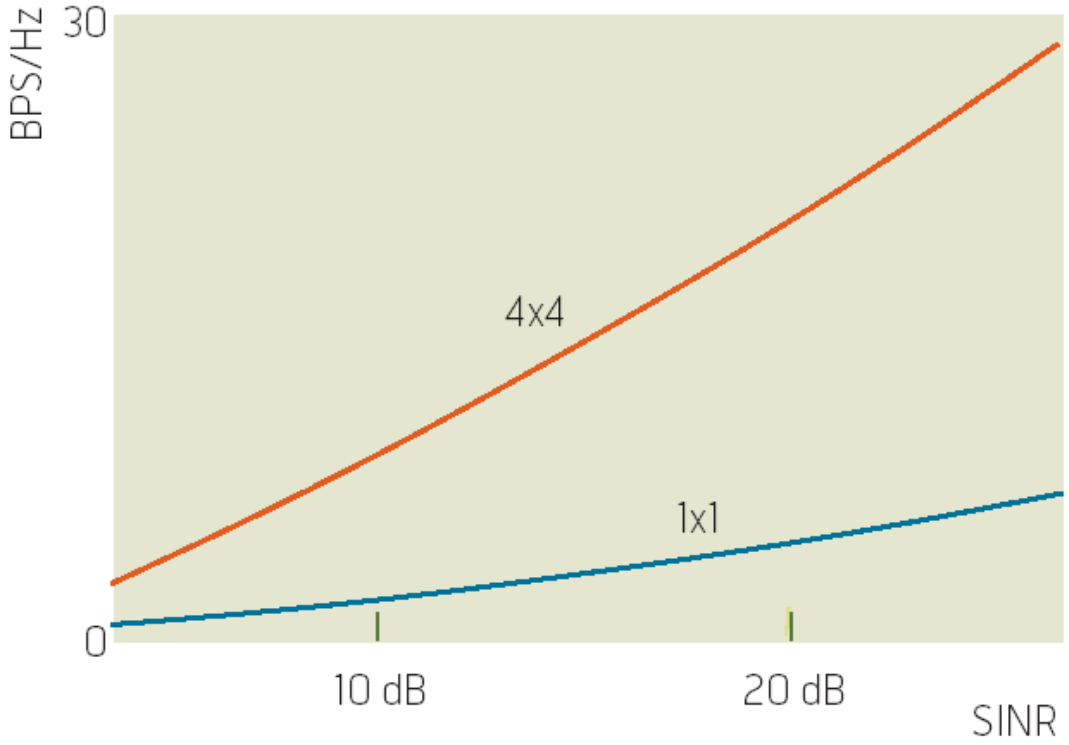


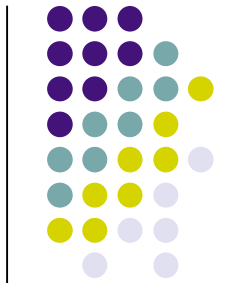
Illustration of spatial diversity gain (2 receive antennas).

MIMO technology, cont'd



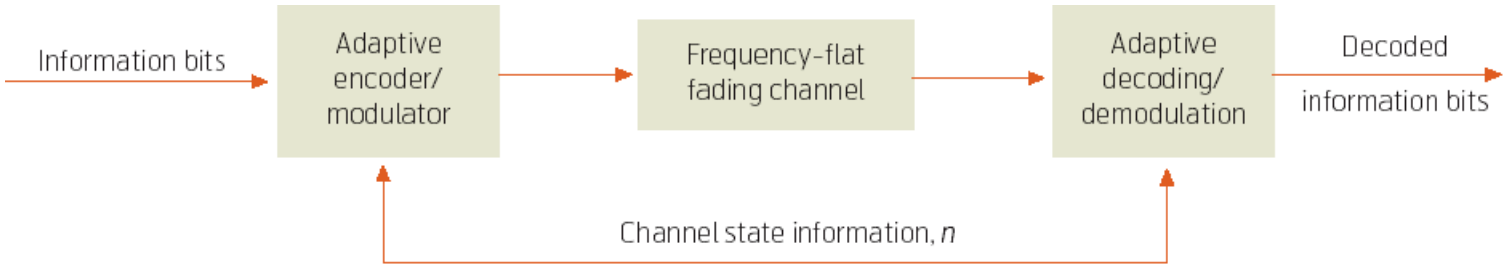
Example of achievable spectral efficiencies for MIMO system with spatial multiplexing (1x1, 4x4).

Link adaptation



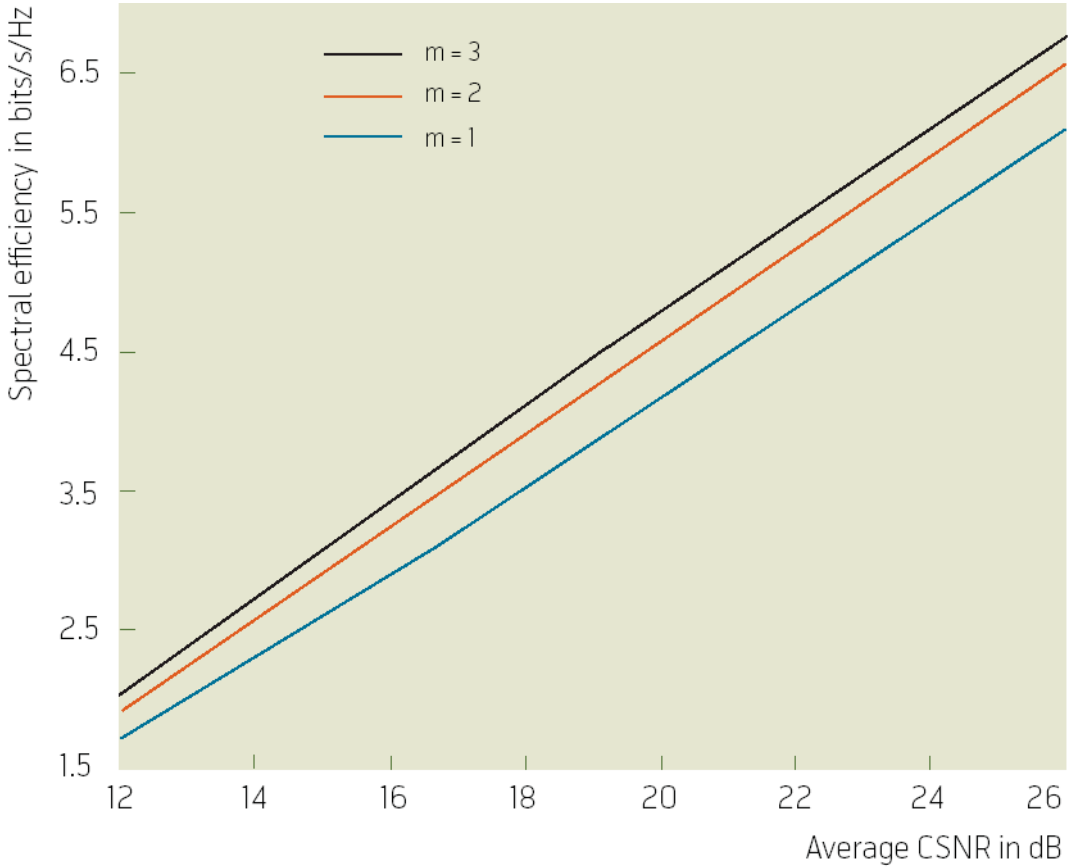
- The quality of mobile radio channels in general varies in time, frequency, and space (multipath fading, shadowing, path loss, terminal mobility,...).
- To exploit channel quality (= transmit maximum average number of bits per second per Hz) we need *adaptive* transmission schemes:
  - Adaptive information rate - i.e., *adaptive coding and modulation*
  - Adaptive transmit power policies
- Transmitter need *channel state information* to update its operational mode according to the channel dynamics.
- Examples of applications: DVB-S2 (Digital Video Broadcasting - Satellite v.2), IEEE 802.16 WiMAX.

Link adaptation, continued



Generic block diagram of an adaptive coded modulation system.

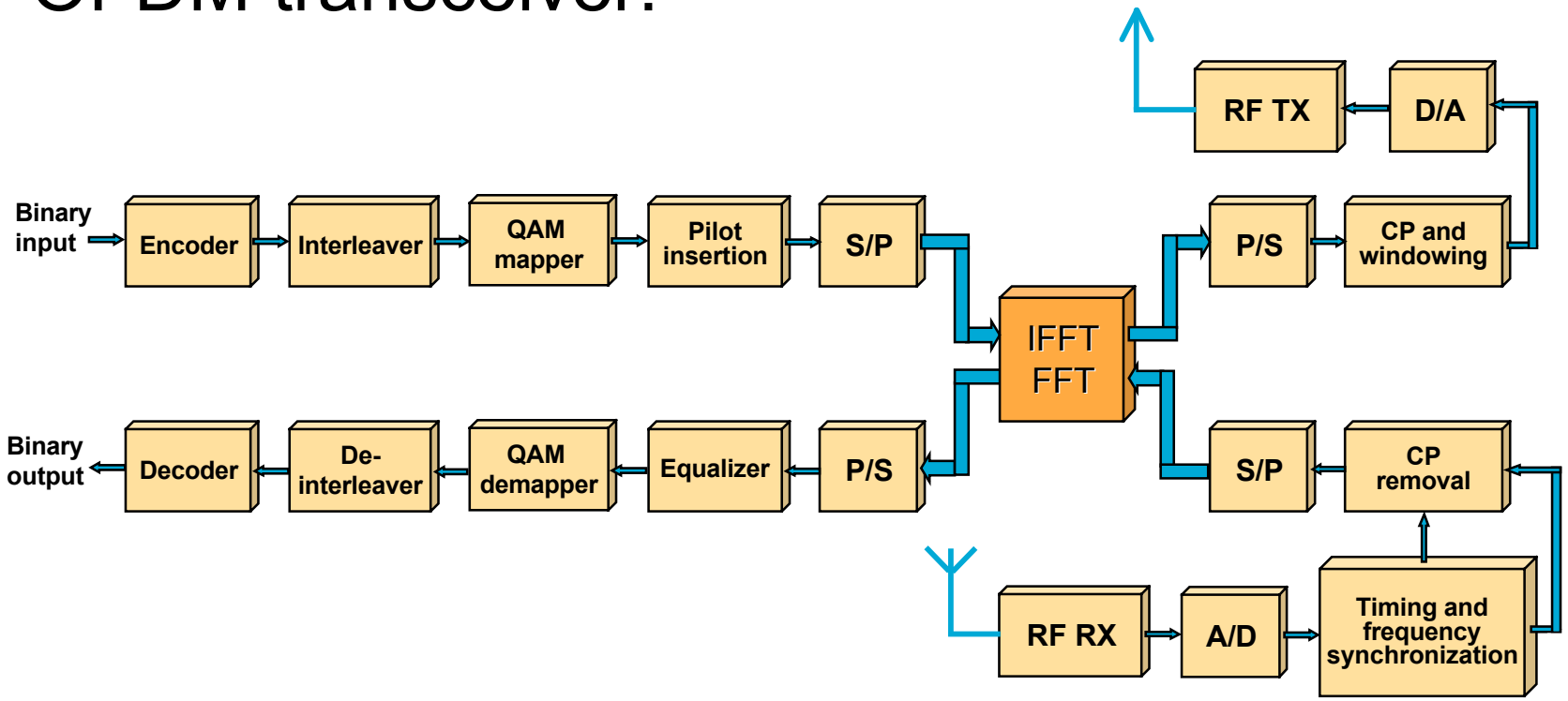
Link adaptation, continued



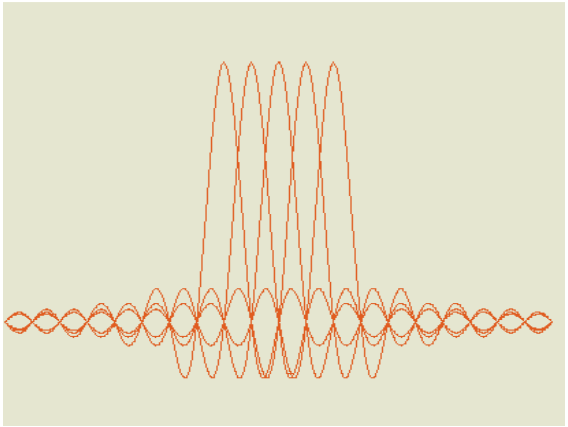
Example of spectral efficiency for an adaptive coded modulation scheme.

Multicarrier-based modulation and access (OFDM)

- OFDM transceiver:

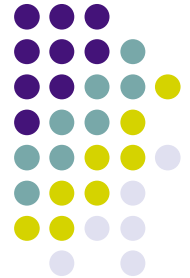


OFDM, continued



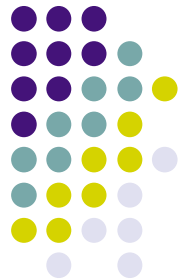
- Relies on *orthogonality* between tightly packed frequency subchannels (created by IFFT).
- Robust against *intersymbol-interference* (ISI); i.e. simple to deal with unwanted effects of frequency-selective channels (no complex equalizers)
- *Efficient use of spectrum* - may also be combined with link adaptation techniques and MIMO.
- *Flexible* - subchannels may be loaded independently.
- May be used both for *modulation and multiple access*, or combined with CDMA (MC-CDMA, among proposals for 4G downlink).
- Caveat: Sensitive to synchronization errors and HPA nonlinearities.

Some current and upcoming OFDM applications



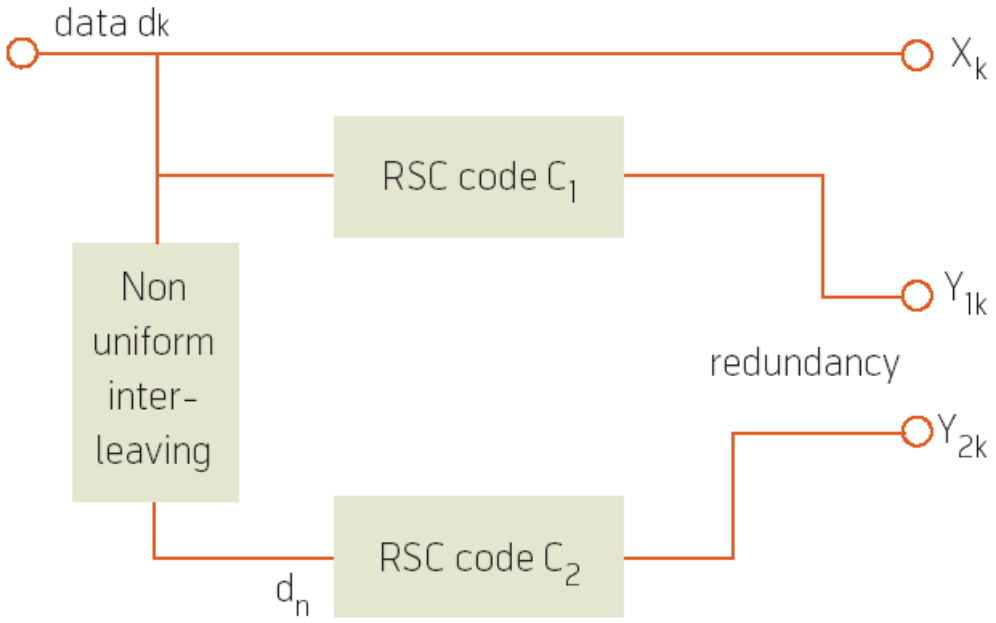
- High-speed digital subscriber lines (HDSL, ADSL, VDSL)
- Digital broadcasting systems (DAB, DVB-T)
- Wireless LANs (e.g., IEEE 802.11a)
- Broadband Wireless Access (IEEE 802.16/ETSI HiperMAN WiMAX)
- Fixed broadband wireless access (IEEE 802.11g)
- Considered for future broadband radio area networks and multimedia communications (European and American projects).

Iterative (”turbo”) receiver processing



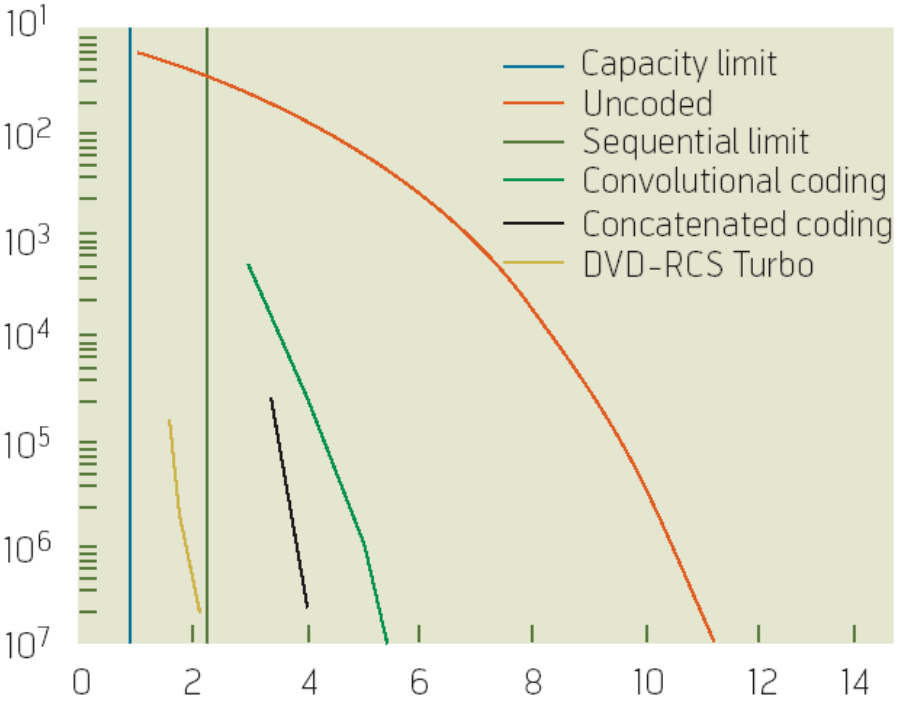
- ”The turbo principle”: Two receiver processing blocks exchange ’soft’ information about their decisions, and about the reliability of these decisions.
- The past decisions and their reliability are then exploited in further processing, in an iterative manner.
- The iterations successively improve reliability, and typically converge towards a near-optimal solution.
- The classic example: Turbo CODING [Berrou et al., 93] - comes within a fraction of a dB of information theoretical limits (used already in UMTS).
- Iterative receiver processing is now also used for (multiuser) detection, synchronization, equalization, joint detection and estimation, and so on.
- Is ”joint, all-iterative receiver processing” the final answer...?

Iterative receiver processing, continued



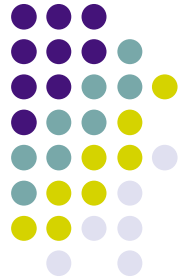
Parallel Turbo encoder
(from Berrou *et al*.)

Iterative receiver processing, continued



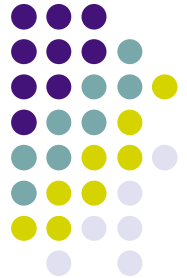
BER performance of some representative coding schemes (courtesy of Nera Research).

Cross-layer design and optimization



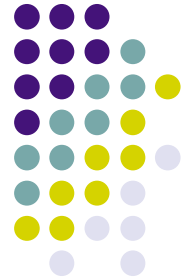
- Today's wireless networks are based on OSI layered protocol architecture: physical layer, link layer, MAC layer, network layer, application layer.
- Very limited communication and interaction between layers: *Modularity, robustness, and ease of design.*
- However *layer behaviours have important interdependencies*: A completely modularized design can therefore be very *suboptimal* with regards to throughput, overhead, energy efficiency, etc.
- Challenge: Improve communication and interaction between layers to improve efficiency, while still keeping benefits of layered design.
- Design *cross-layer protocol*, supporting information exchange, adaptivity, and optimization across (as well as within) layers.

Cross-layer optimization, examples



- Adaptive channel coding and hybrid-ARQ techniques based on channel state information (CSI) and end-to-end ACKs.
- Opportunistic medium access control (multi-user scheduling) based on link-level CSI, fairness and QoS constraints
- Adaptive routing based on dynamics in link, network, and traffic conditions
- Joint source-channel coding based on information exchange between application and link layer (QoS constraints and CSI)
- Energy-optimized joint design of circuitry and transmission schemes (NB - short-range applications!)

What about UMTS (W-CDMA)?



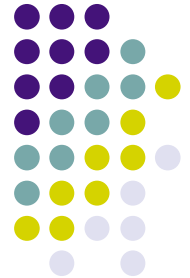
- Recent research shows: The current standard has *fundamental capacity limitations for high user loads* (many users operating simultaneously) [Shamai, Verdú, Müller 01 - 04]

- When the number of active users increases beyond a certain point, the aggregate system capacity (summed over all users) start decreasing if more active users are added....!

(This deficiency can in principle be fixed by modifications to the current standard - but for maybe a tenfold increase in complexity, for only a doubling in capacity.)

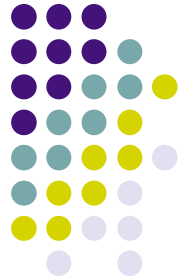
- Still: *Completely new standard is needed for significant capacity increase.*

What about Ultra-Wideband (UWB)?



- Def: A signal is UWB if bandwidth is > 0.25 x carrier frequency.
- UWB candidate for energy-efficient short-range communications (low power density, robust to narrowband interference)
- *But:* Very large bandwidths on fading channels cannot be efficiently utilized by spreading power ”uniformly” in both time and frequency [Telatar/Tse 00, Médard/Gallager 02, Subramanian/Hajek 02].
- Capacity for such schemes asymptotically approaches *zero*!
- For high throughput on such channels, signals must be ”peaky” in time and/or frequency - i.e. *localize* power in time/ frequency.
- This casts serious doubts on W-CDMA as the design choice for future wideband systems....!
- *Frequency-hopping* wideband systems (e.g. FH-CDMA, multiband OFDM), if properly designed, do not have these limitations.

Summary and conclusions



- Have discussed some of the most promising radio technologies for inclusion on wireless and mobile communication systems beyond 3G (4G).
- Impact of 3G is still uncertain.....???
- 4G is still at research stage, available after 2010?
- Employing the discussed techniques, 4G has a significant potential for capacity improvements over 3G systems.
- 4G will be an amalgam of many different systems, including existing systems for mobile, WLAN, fixed wireless access, satellite communications, and wired solutions (DSL, fibre).
- IP-based, capacity-demanding, multimedia data traffic.