4G MOBILE BROADBAND – LTE

PART I

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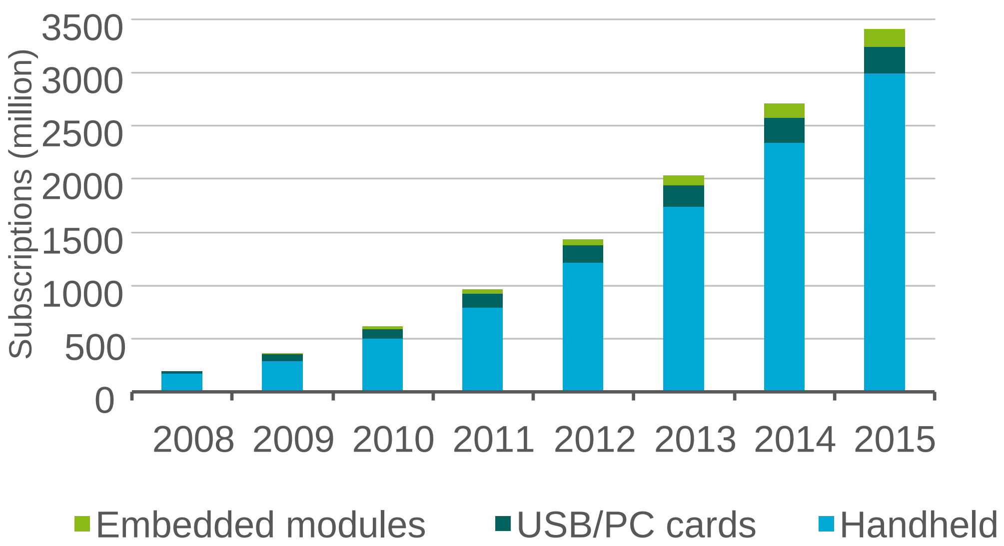
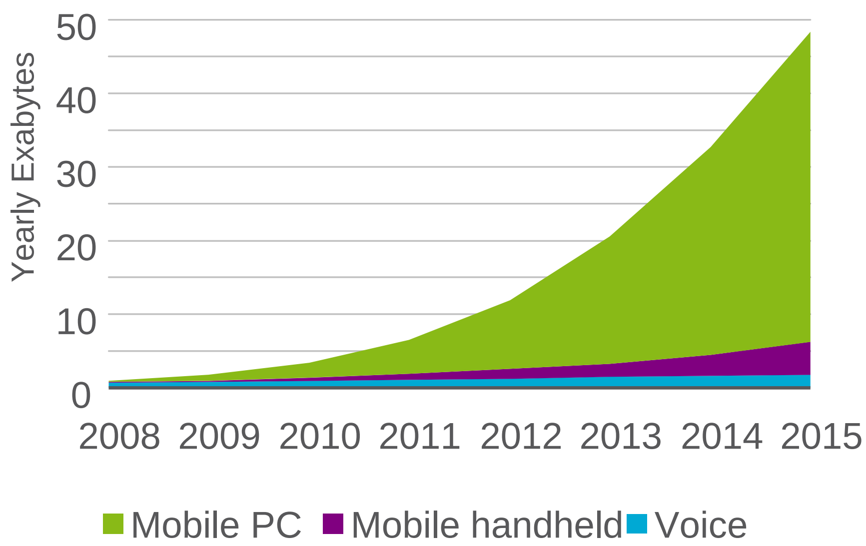
DATA OVERTAKING VOICE

› Data is overtaking voice...
...but previous cellular systems designed primarily for voice

Rapid subscriber growth



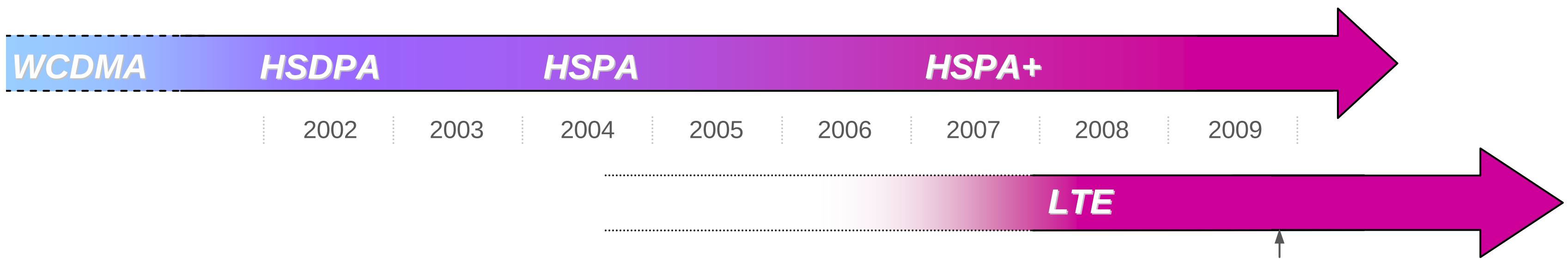
Rapid traffic growth



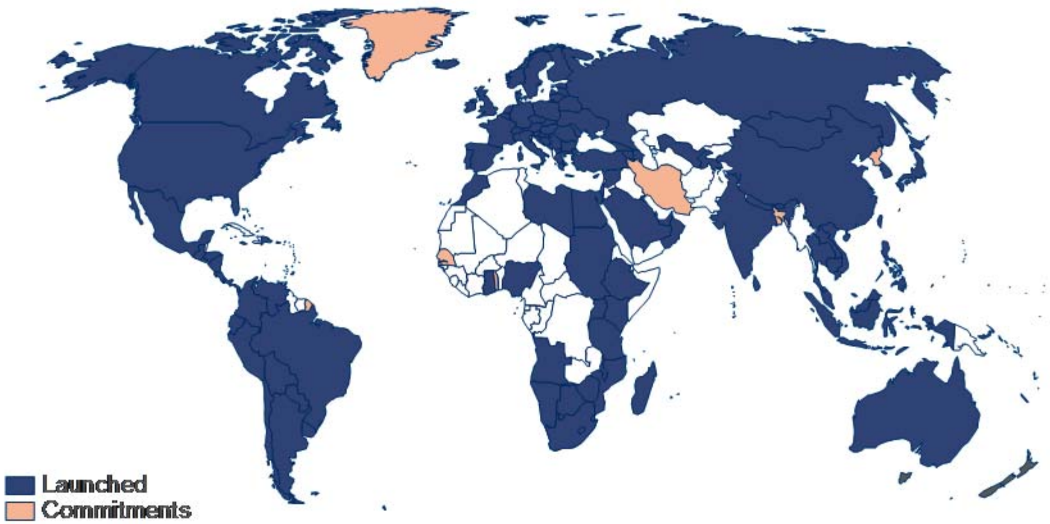
MOBILE BROADBAND

- HSPA – High-Speed Packet Access (”Turbo-3G”)
  - Evolution of 3G/WCDMA
  - Data rates up to ~168 Mbit/s (DL), ~44 Mbit/s (UL)
  - Support for broadcast services (IMB)

- LTE (”4G”)
  - Very high data rates in a wide range of spectrum allocations
  - Data rates up to 300 Mbit/s (DL), 75 Mbit/s (UL) in frist version
  - Integral support for broadcast services



THE 3GPP ECOSYSTEM



333 HSPA operators in 139 countries…

2922 HSPA devices from 255 suppliers…

Source: GSA, WCIS/Informa, and Infonetics

OUTLINE

Series of three seminars

I. Basic principles
   - Channel and traffic behavior
   - Link adaptation, scheduling, hybrid-ARQ
   - Evolving 3G, inclusion of basic principles in WCDMA

II. LTE
   - First step into 4G
   - Path towards IMT-Advanced

III. Standardization
   - How are HSPA and LTE created?
   - 3GPP, ITU, ...

RADIO CHANNELS AND PACKET DATA – SOME PROPERTIES

WIRELESS VS WIRELINE

- Wireless seems simple…

$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

- …so what's the problem?

WIRELESS VS WIRELINE

- Many aspects are similar…
  …but there are some fundamental differences!

Wireline

- Cable
- “No” spectrum limitation
  - Over-provisioning
- Relatively static channels
  - No fading
- Congestion ➡ lost packets
- No mobility

Wireless

- No cable ☺
- Spectrum is scarce
  - Radio-resource management
- Time-varying radio channel
  - Fast fading
- Fading ➡ lost packets
- Mobility

RADIO-CHANNEL VARIATIONS

- Transmitted power P_{Tx} ➡ received power $P_{Rx} << P_{Tx}$

- Path loss $\propto 1/r^{\alpha}$ $\quad \alpha \approx 2 \cdots 3.5$
  - Given by Tx-to-Rx distance

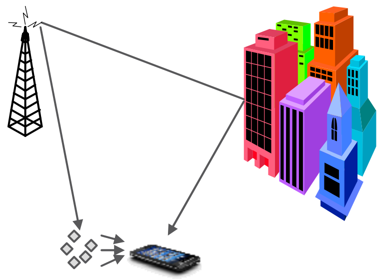
- Log-normal fading
  - Due to random variations in terrain (large scale)
  - Received signal strength in dB given by normal distribution

- Fast fading
  - Random variations in environment
  - Often modeled by a Rayleigh distribution

Slow

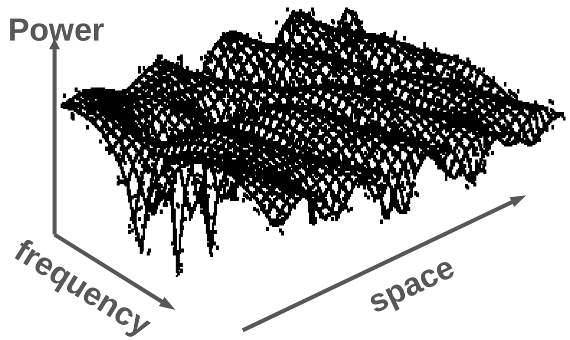
Fast

RADIO-CHANNEL VARIATIONS



- Transmitted signal reflected in numerous objects
  - Multiple delayed signal copies received
  - ’Large’ and ’small’ time differences between components
- ’Small’ delay difference
  - components add constructively...
    ...or destructively
  - Large number of components
    ➡ central-limit theorem
    ➡ Gaussian-distributed amplitude
    ➡ Rayleigh-distributed power
    (Rayleigh-fading, fast fading)

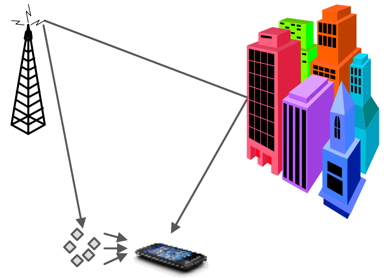
Multi-path fading

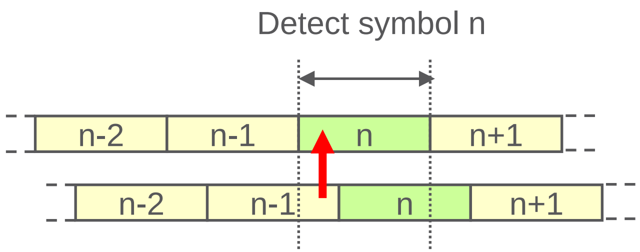


Radio-channels – rapidly varying signal quality

RADIO-CHANNEL VARIATIONS

- ’Large’ delay difference
  - Inter-symbol interference (ISI)





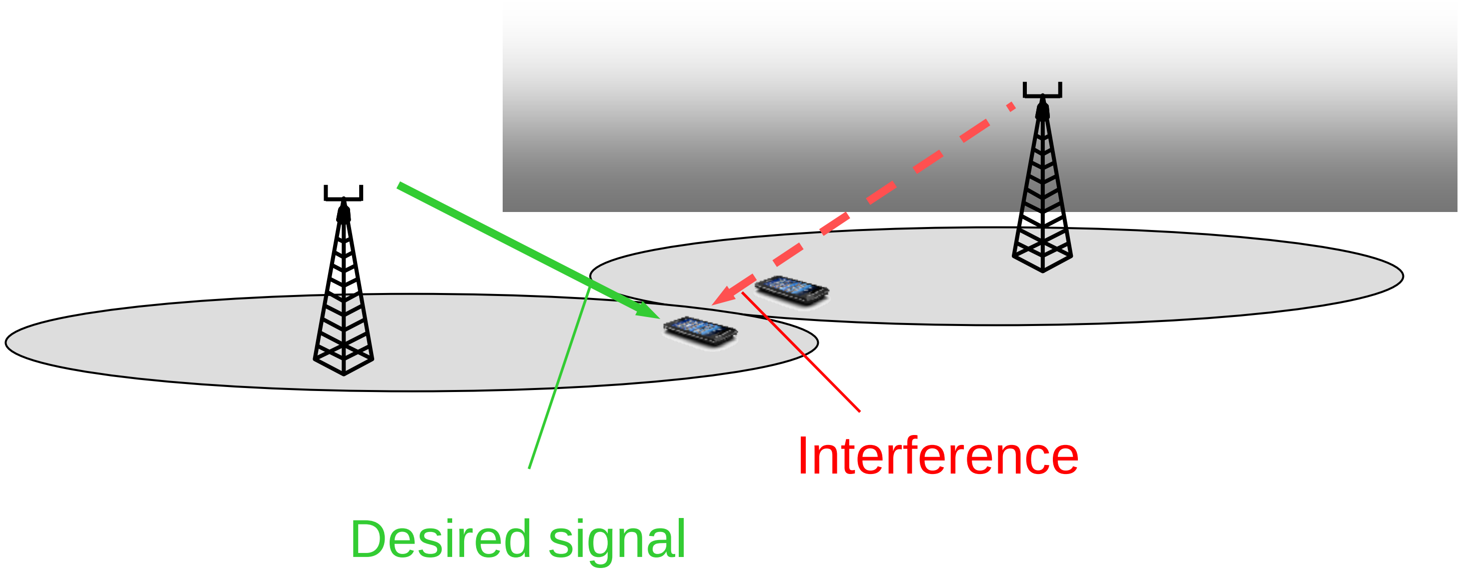
Intersymbol interference

Example:
1 Mbit/s bit rate ➡ bit duration 1 µs − same order as time dispersion

- Handling time dispersion through...
  ...receiver-side signal processing (e.g equalizer)
  ...transmission scheme robust to time dispersion (e.g. OFDM)

INTERFERENCE VARIATIONS

› Transmissions in neighboring cells cause interference
  ➡ received signal quality affected by neighboring cell activity



TRAFFIC VARIATIONS

› Traditional voice services
  – Low, ~10 kbit/s data rate
  – Fairly constant during the call

} ➡ circuit-switched ok!

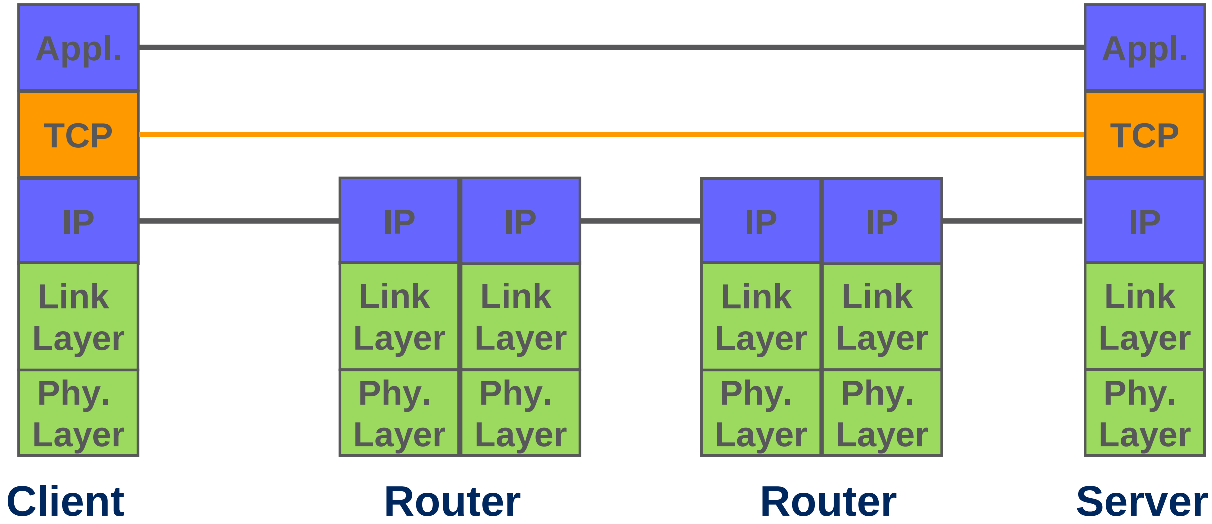
› Packet-data services
  – Behavior depends on type of service
  – Typically rapidly and randomly varying rate requirements
  ('all-or-nothing' resource requirement)

} ➡ packet-switched NW

Packet-data systems – rapidly varying data rates

TCP BASICS

› TCP – Internet's end-to-end transport layer protocol (non-real time)



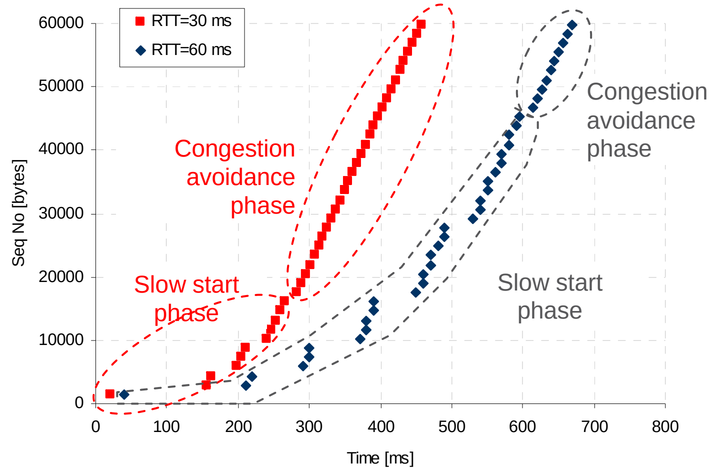
› Main responsibilities of TCP:
  – provide reliable data transport
  – avoid congestion in the network

Interaction with wireless links requires attention!

TCP BASICS

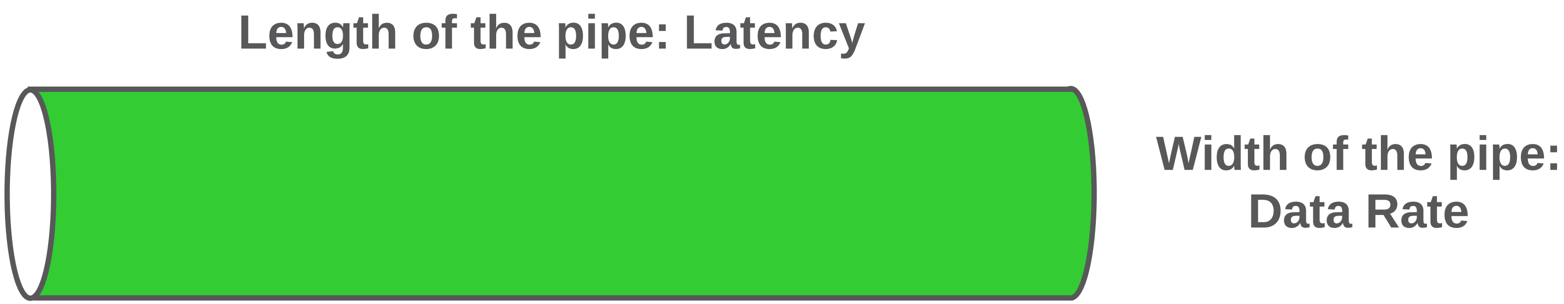
- Error recovery and congestion control are intertwined
  - lost packets are used as congestion signal by TCP
    ➡ radio-link errors should be 'hidden' from TCP
  - Lost packets ➡ timeout ➡ slow start

- TCP congestion management
  - Window = not-yet-ACKed packets in transmission
  - Phase 1: Slow start
    - Increase window by one on each received ACK
    - window grows exponentially
  - Phase 2: Congestion avoidance
    - Increse window by 1/window_size on each ACK
    - window grows linearly



TCP BASICS

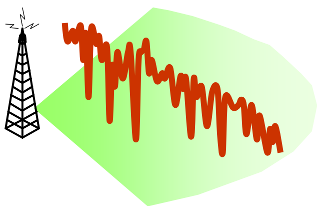
- TCP performance determined by data rate *and* latency
  - High data rate alone not sufficient – need low latency as well
  - Delay-bandwidth product



High data rate ***and*** low latency

RADIO CHANNELS AND PACKET DATA

- Radio-channel quality varies...
  - ...distance to base station
  - ...random environmental variations
  - ...interference variations
- Traffic pattern varies...
  - ...user behavior
  - ...server load



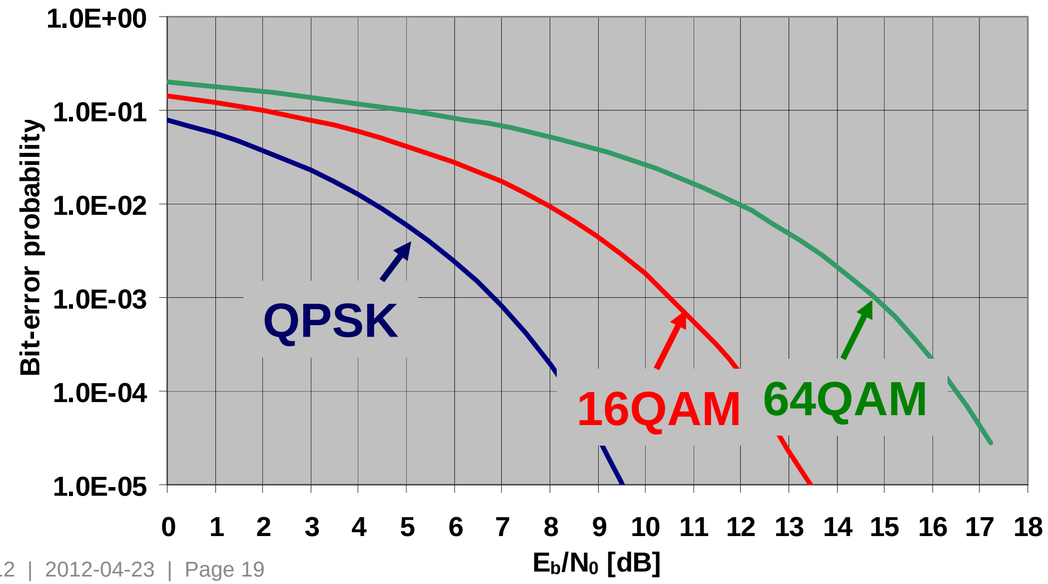
Adapt to **and** ***exploit*** **channel and traffic variations!**

BASIC PRINCIPLES USED BY HSPA AND LTE

RATE CONTROL

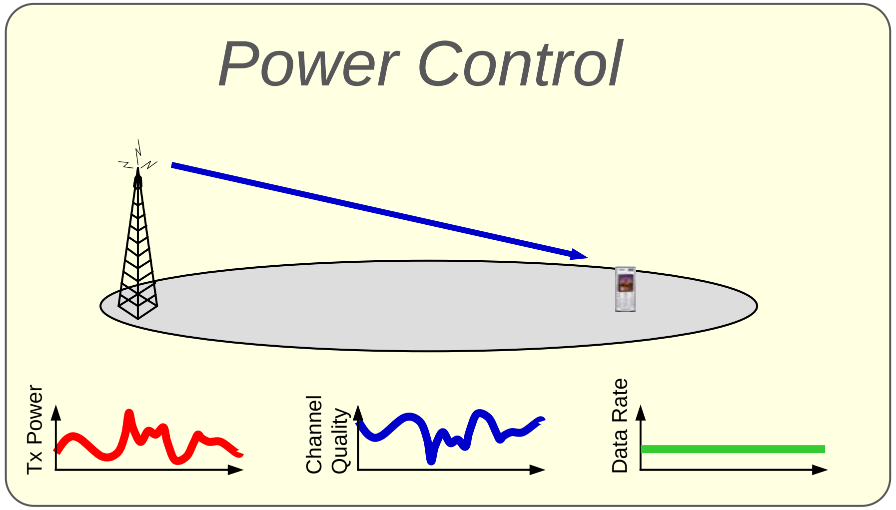
› E_b/N_0 – fundamental quantity in communications
  - E_b received energy per information bit [J]
  - N_0 noise power spectral density [W/Hz]

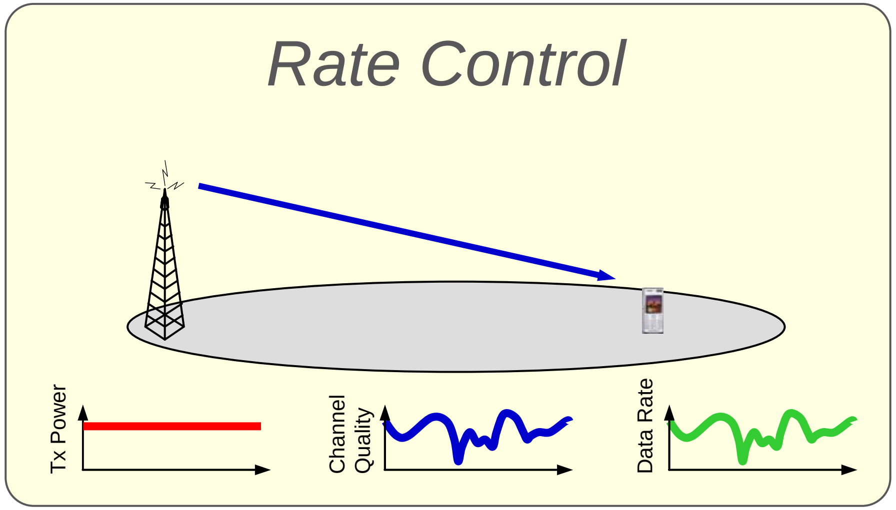
› Block-Error Rate vs E_b/N_0
  - Practical schemes – BLER decreases with increasing E_b



RATE CONTROL

- N_0 is given
  - Noise etc
- How to control E_b despite varying radio-channel quality?
  - $E_b = P \bullet T = P / R$





RATE CONTROL

- Packet-data services typically accept (short-term) data-rate variations
  - Internet has unpredictable data rates
  - Short-term variations acceptable even for most services with strict QoS requirements – only cares about average data rate

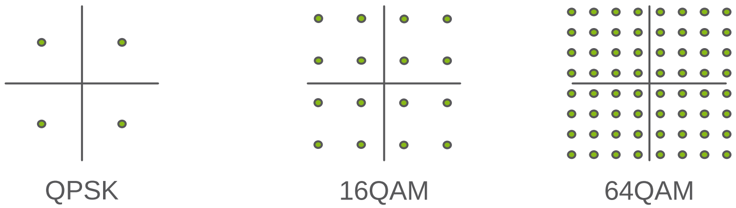
- Rate control more efficient than power control
  - Power amplifier runs at ’full power all the time’

RATE CONTROL

- Data rate controlled through...

- ...different channel coding rates
  - Advantageous channel conditions ➡ high code rate
  - Code rates from 1/3 to ~1

- ...different modulation schemes
  - Advantageous channel conditions ➡ higher-order modulation

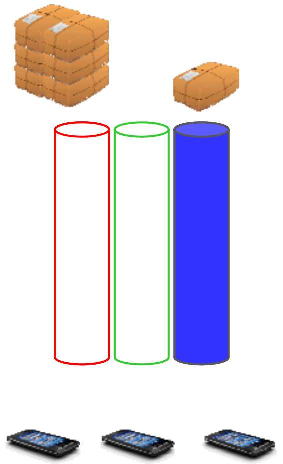


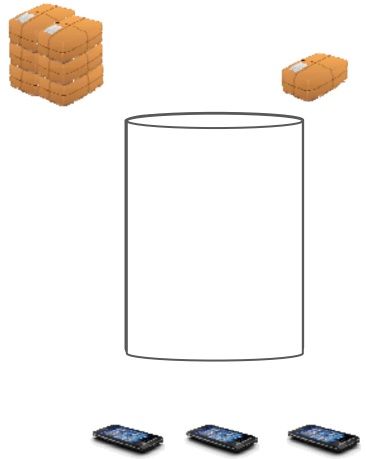
- ...different multi-antenna schemes

SHARED-CHANNEL TRANSMISSION

- Dedicated channel
  - Resources assigned at ”call setup”
  - Independent of instantaneous traffic
  - ”Circuit-switched”

- Shared channel
  - Dynamic sharing of common resource
  - Adapts to instantaneous traffic situation
  - ”Packet-switched”



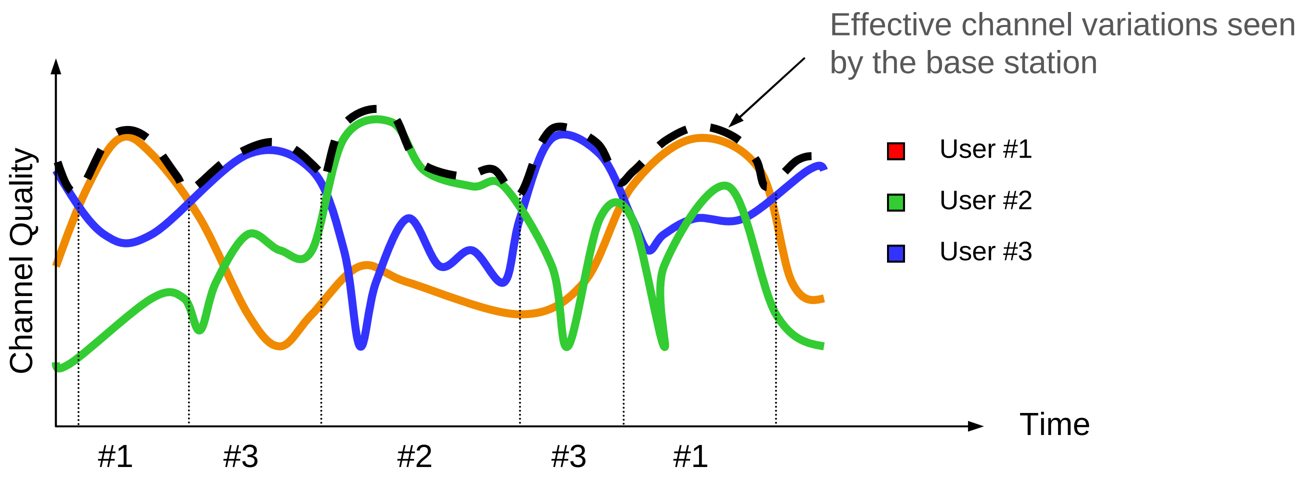


Shared channel – dynamic resource management

CHANNEL-DEPENDENT SCHEDULING

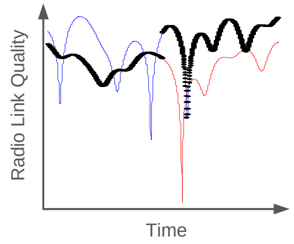
- Scheduling determines at each time instant…
  - …to whom to assign the shared channel
  - …which data rate to use (rate adaptation)

- Basic idea: transmit at fading peaks
  - Known as multi-user diversity

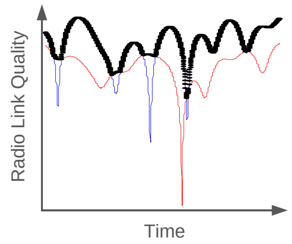


CHANNEL-DEPENDENT SCHEDULING

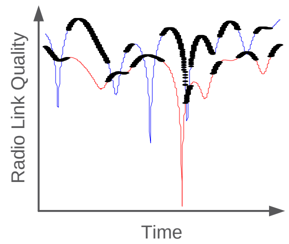
- Round Robin (RR)
  - Cyclically assign the channel to users ***without*** taking quality conditions into account
  - Simple but poor performance



- Max C/I
  - Assign the channel to the user with the best ***absolute*** quality
  - High system throughput but not fair



- Proportional Fair (PF)
  - Assign the channel to the user with the best ***relative*** quality
  - High throughput, fair



CHANNEL-DEPENDENT SCHEDULING

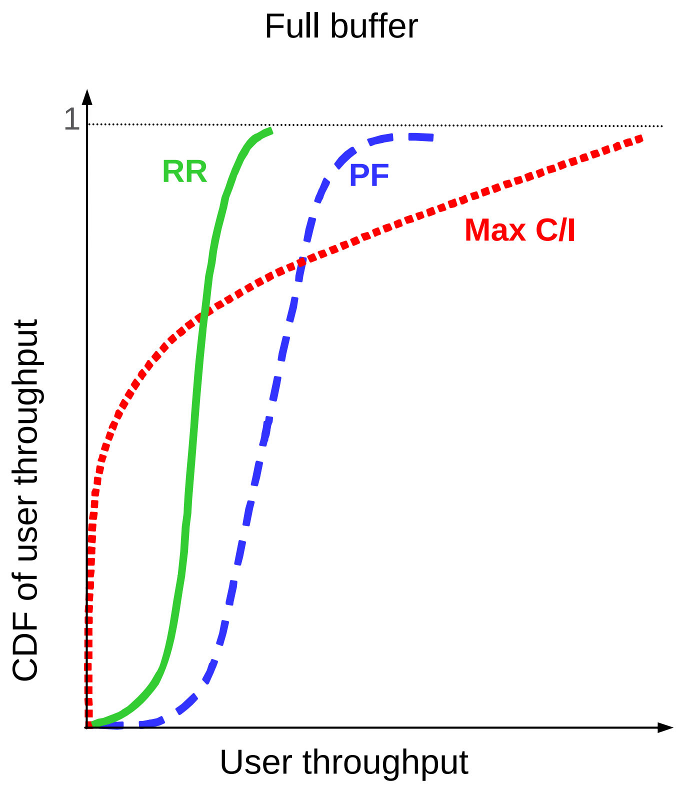
- Good schedulers take radio *and* traffic variations into account

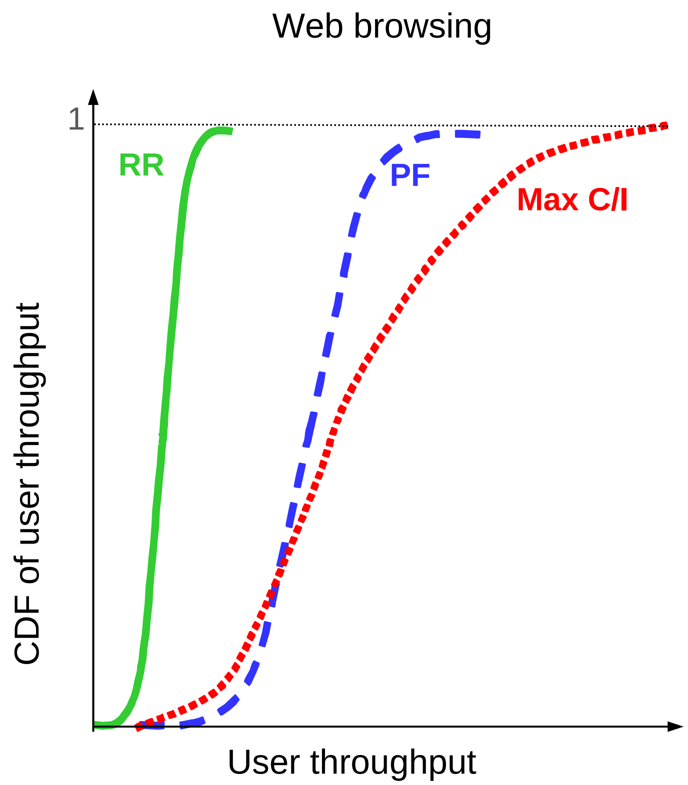
- Radio-channel variations
  - Schedule at fading peaks

- Traffic variations
  - Schedule when user has data
  - May take priorities into account
    - Example: VoIP has higher priority than file download

CHANNEL-DEPENDENT SCHEDULING

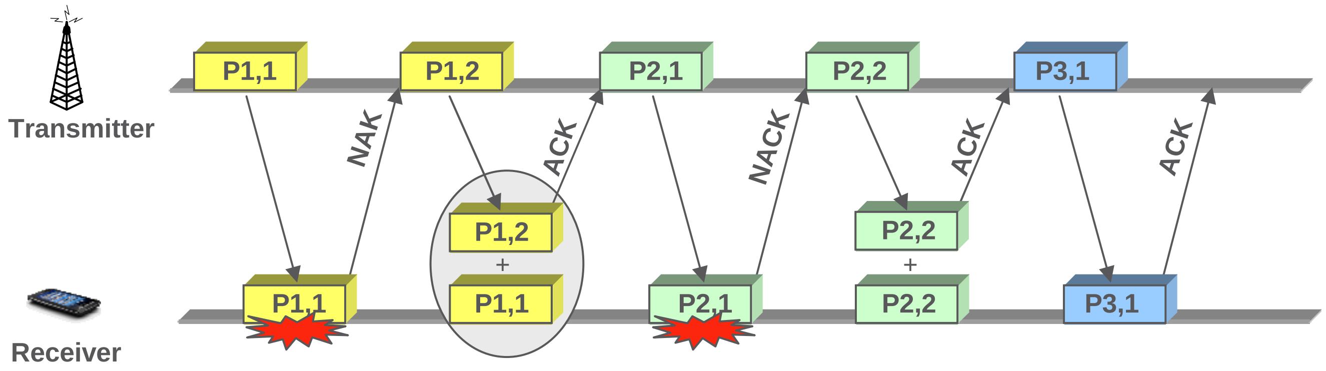
› The larger the unfairness, the higher the system throughput...
...true for full buffers but realistic traffic complicates the picture





HYBRID ARQ WITH SOFT COMBINING

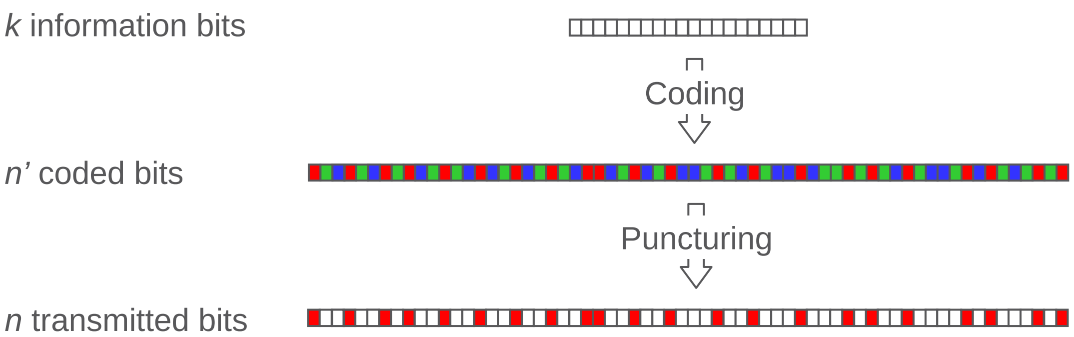
- Retransmission of erroneously received packets
  - Fast ➡ no disturbance of TCP behavior
- Soft combining of multiple transmission attempts
  - Soft combining ➡ improved performance



HYBRID ARQ WITH SOFT COMBINING

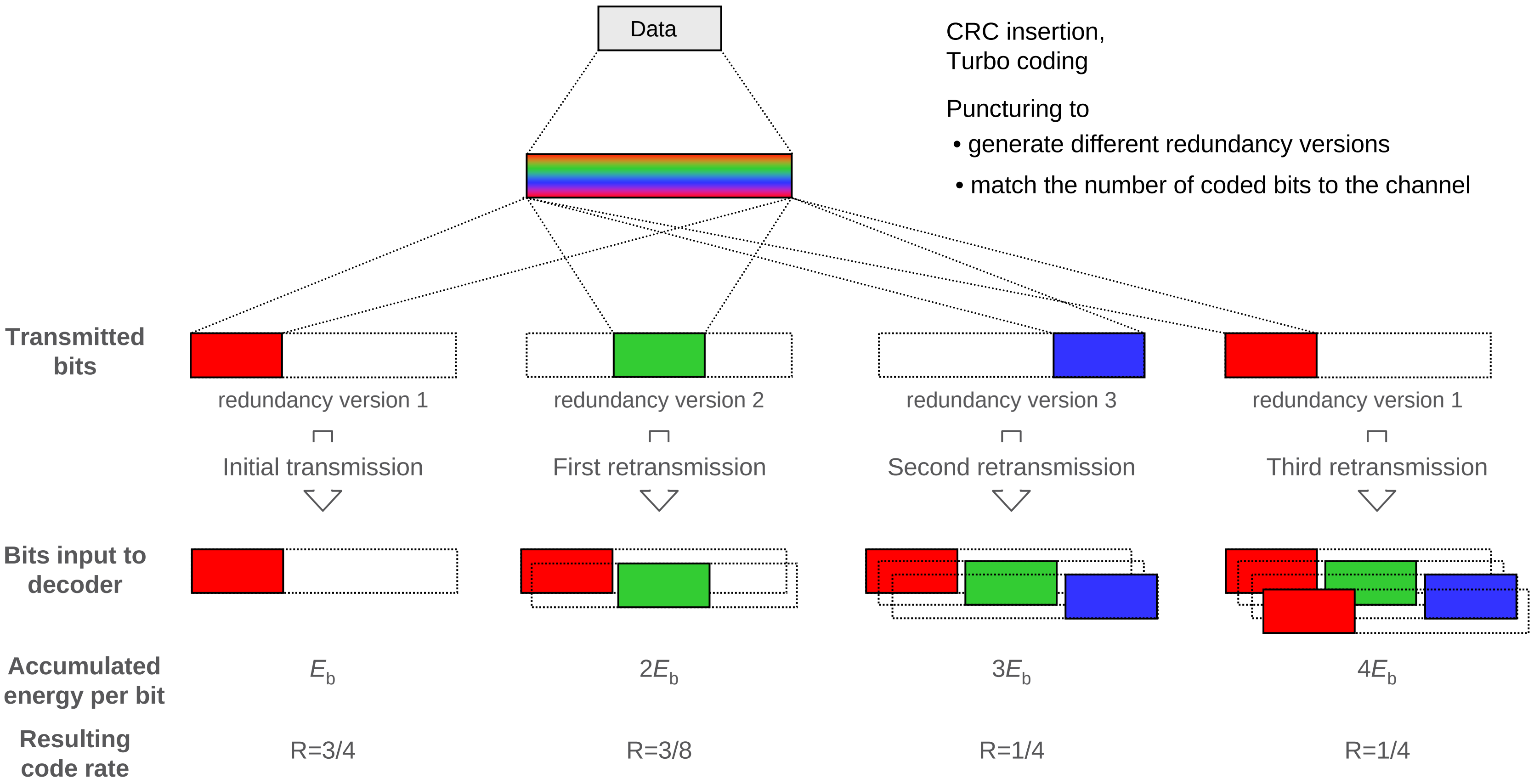
- Coding
  - Add redundancy at transmitter
  - Exploit redundancy at receiver to correct (most) transmission errors
  - Code rate R = k/n, code rate fine tuned by puncturing
  - The lower the code rate R, the lower the error rate but the higher the overhead

- Hybrid-ARQ
  - Correct most errors with coding
  - Detect uncorrectable transmission errors, request retransmissions



HYBRID ARQ WITH SOFT COMBINING

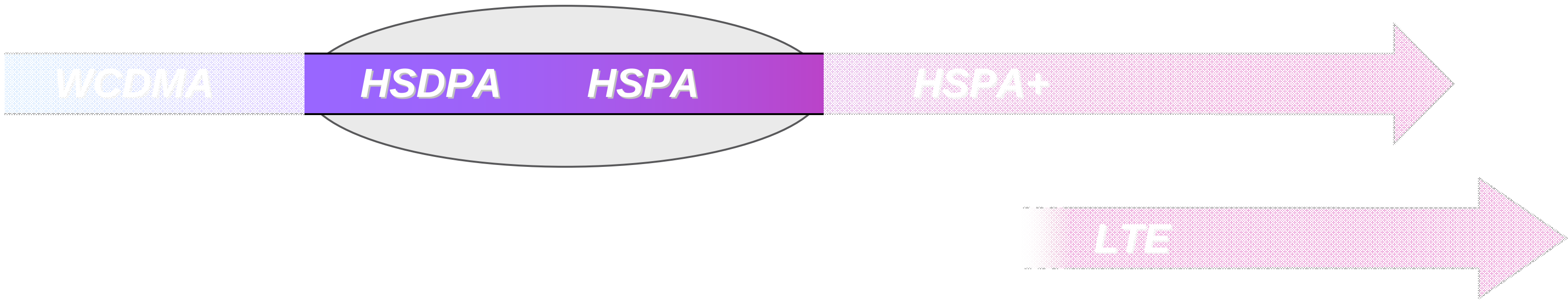
› Incremental redundancy



ERICSSON

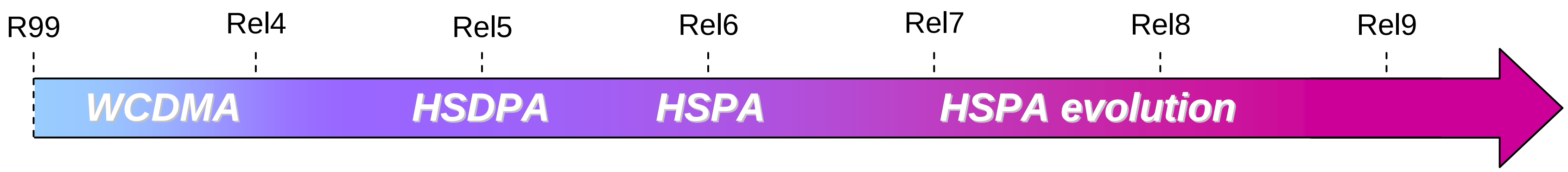
HSPA

HIGH-SPEED PACKET ACCESS

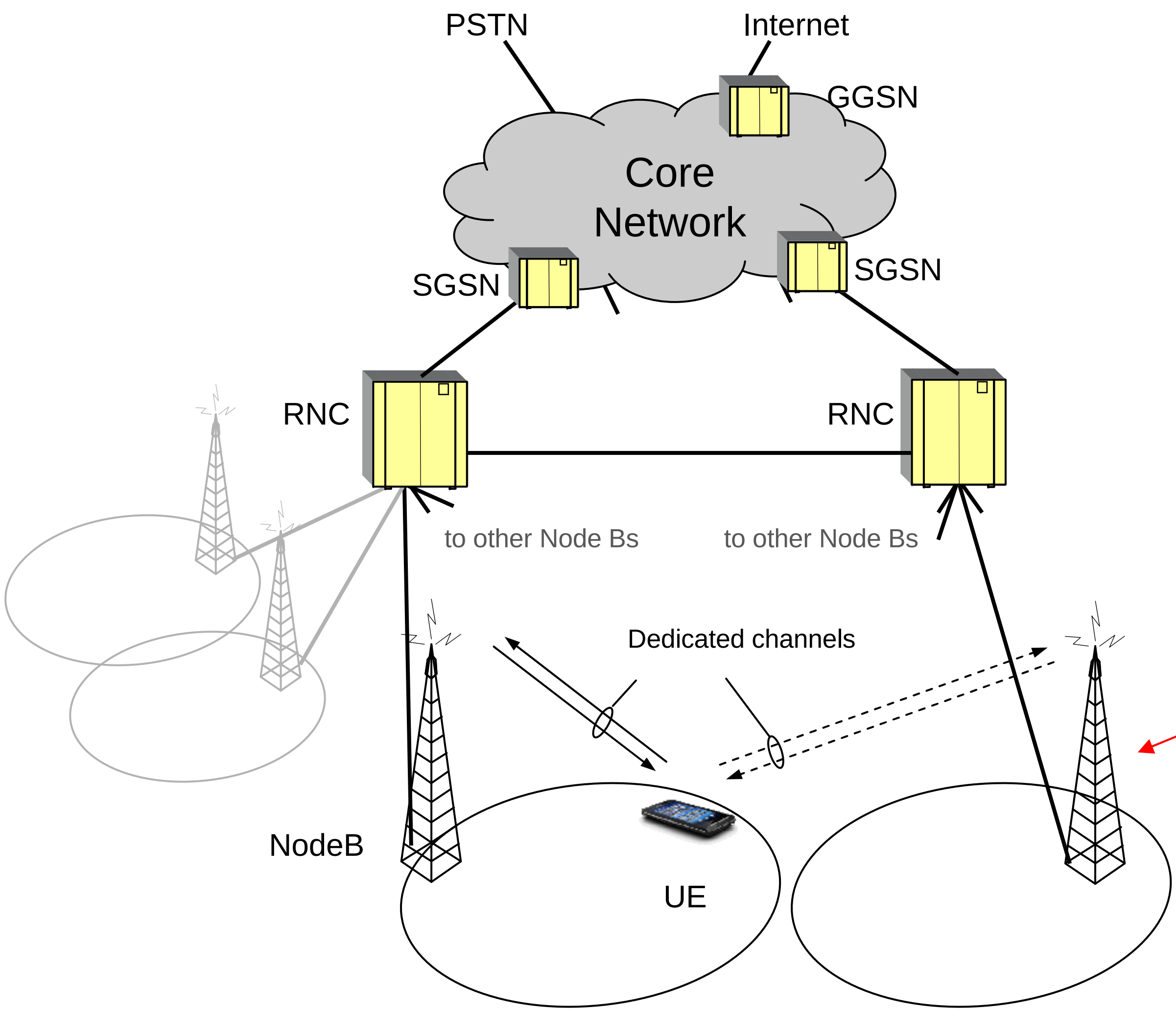


WCDMA BACKGROUND

- WCDMA (”3G”)
  - Basics developed mid-90’s, standard ready -99
  - Circuit-switched voice
  - ”ISDN-like” packet data (typically up to 384 kbit/s)
- HSPA (”Turbo-3G”)
  - Packet-data improvement add-on to WCDMA
  - First version ~2002, still evolving
  - Data rates up to 168 Mbit/s (downlink), 44 Mbit/s (uplink)
- HSPA is an *evolution* of WCDMA
  - Incorporating the basic principles in an existing 3G network



ARCHITECTURE
WCDMA/HSPA

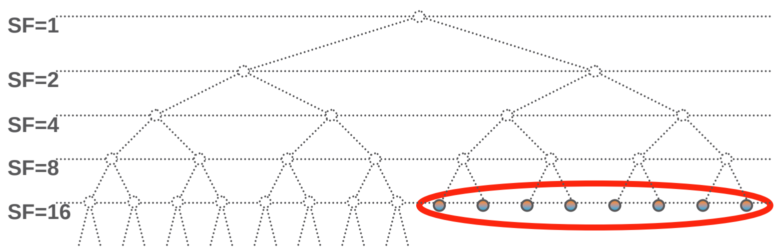


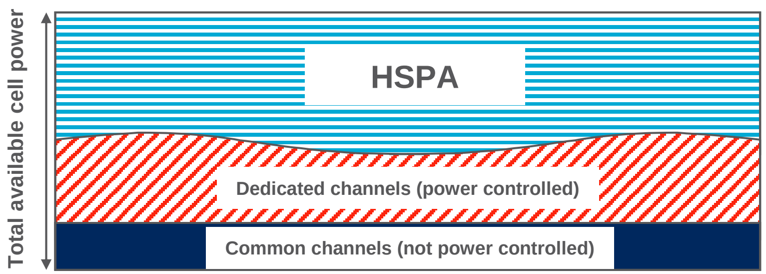
Admission control, call set-up, radio-resource management, retransmission handling...

Fast, dynamic adaptation to radio-channel variations
➡ **new NodeB functionality**
scheduling, rate adaptation, hybrid-ARQ

HSPA BASICS – DOWNLINK

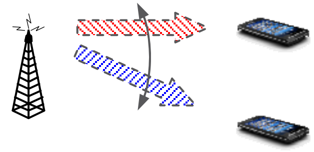
- WCDMA
  - At call set-up, each user is assigned an orthogonal spreading code
  - Spreading factor ➡ data rate
- HSPA – *evolution* of WCDMA
  - Shared set of channelization codes
  - Multi-code transmission



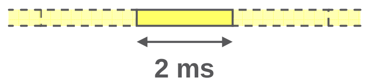


HSPA BASICS – DOWNLINK

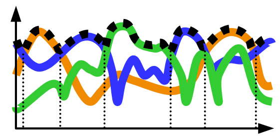
› Shared channel transmission
  – Dynamically shared code resource



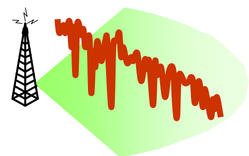
› Short (2 ms) TTI
  – Reduced delays



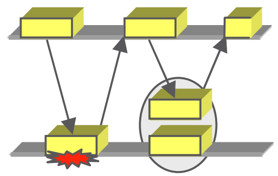
› Channel-dependent scheduling
  – 2 ms basis



› Rate control
  – 2 ms basis

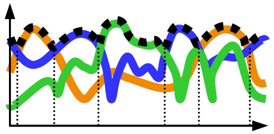


› Hybrid-ARQ with soft combining
  – Roundtrip time of 12 ms possible



DOWNLINK SCHEDULING

› Each code covers full bandwidth
➡ channel-dependent scheduling in time-domain only
  - No access to frequency domain



› Downlink scheduler controls...
  - ...to which user to transmit
  - ...the set of codes to use
  - ...the modulation scheme to use (QPSK, 16QAM, 64QAM)
  - ...the code rate to use

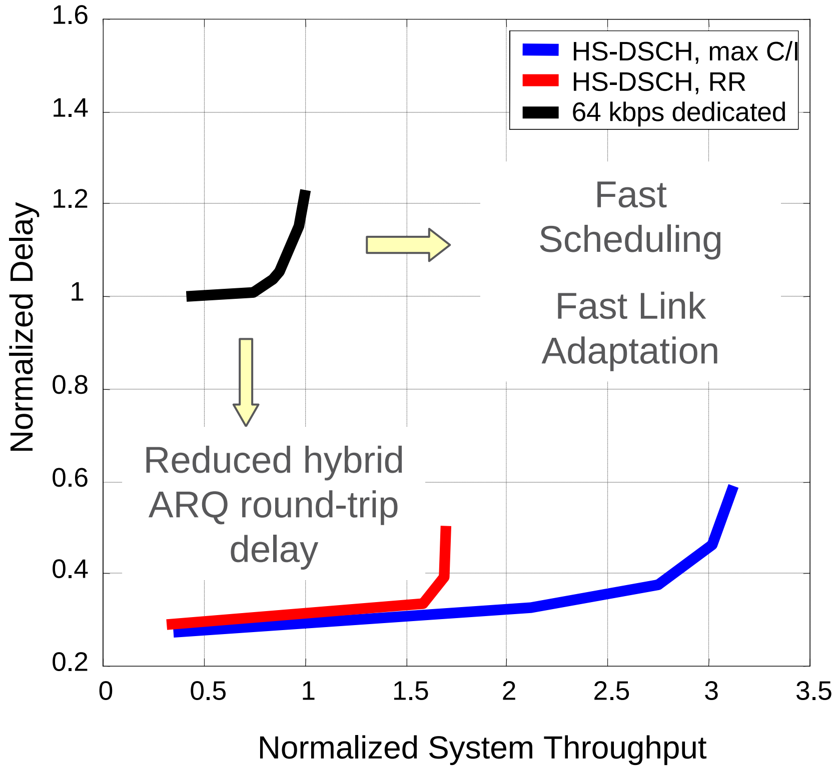
...for each 2 ms transmission interval

› Scheduling decision informed to terminals on a shared control channel
  - All terminals monitor shared control channels for scheduling decisions

PERFORMANCE EXAMPLE

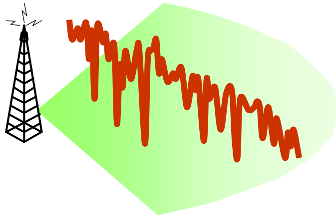
- ~3 times capacity increase
  - for web browsing
  - less for streaming
- ~3 times lower download time
  - for web browsing
  - large TCP objects (file transfer) can show even larger performance gains
- Scheduling strategy has a large impact on the performance.

Web browsing, PedA channel model



SUMMARY

› Radio channel quality is time varying



› Traffic pattern is time varying

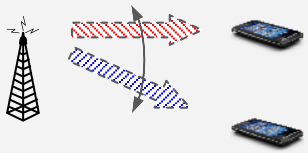
› ***Adapt to*** and ***exploit***…

– variations in the radio channel quality

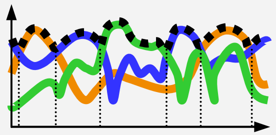
– variations in the traffic pattern

…instead of combating them!

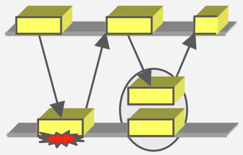
SUMMARY



Shared channel transmission



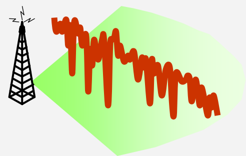
Channel-dependent scheduling



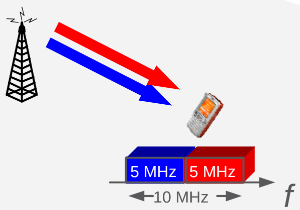
Hybrid ARQ

HSPA (“Turbo-3G”)

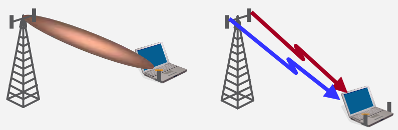
- Packet-data add-on to WCDMA
- First version ~2002, still evolving



Rate control

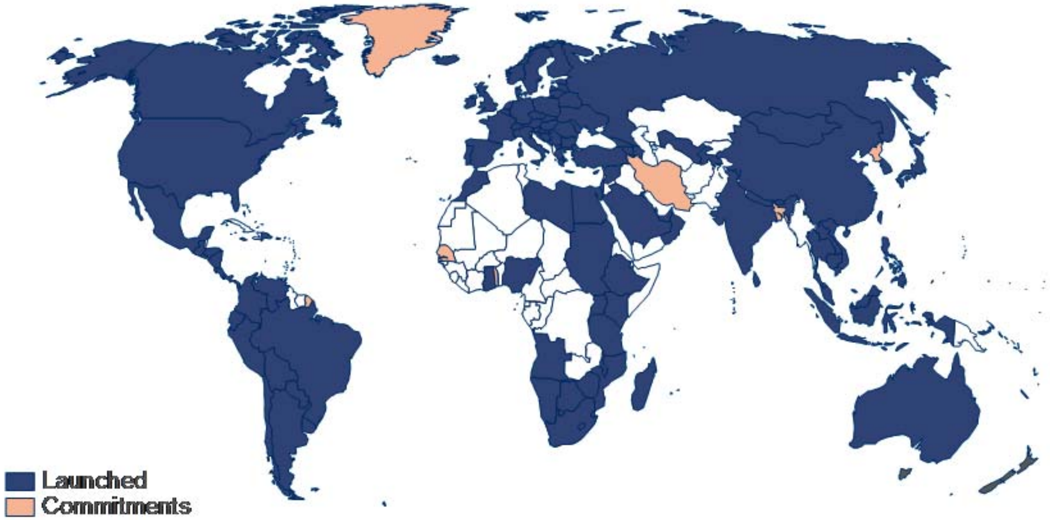


Multi-carrier transmission



Multi-antenna support

SUMMARY – 3GPP ECOSYSTEM



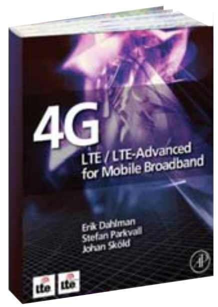
333 HSPA operators in 139 countries…

2922 HSPA devices from 255 suppliers…

Source: GSA, WCIS/Informa, and Infonetics

FOR FURTHER INFORMATION...

Open the 3GPP specifications...



...or read The Book!

Available in English, Chinese, Korean and Japanese.

ERICSSON