4G MOBILE BROADBAND – LTE

PART I

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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 first 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
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?
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 $P_{Tx}$ $\Rightarrow$ received power $P_{Rx} << P_{Tx}$

- Path loss $\propto \frac{1}{r^\alpha}$ $\alpha \approx 2 \cdots 3.5$
  - 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
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)

Radio-channels – rapidly varying signal quality
Radio-Channel Variations

› 'Large' delay difference
  – Inter-symbol interference (ISI)

Detect symbol n

Intersymbol interference

Example:
1 Mbit/s bit rate $\Rightarrow$ 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)
Transmissions in neighboring cells cause interference
- received signal quality affected by neighboring cell activity

**INTERFERENCE VARIATIONS**

Interference

Desired signal
TRAFFIC VARIATIONS

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

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

⇒ circuit-switched ok!

⇒ 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
    - Increase 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

**Length of the pipe: Latency**

**Width of the pipe: Data Rate**

High data rate *and* low latency
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?
  - $E_b = P \cdot T = P / R$

**Power Control**

**Rate Control**
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

  QPSK 16QAM 64QAM

› ...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"
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

[Diagram: Effective channel variations seen by the base station]
- User #1
- User #2
- User #3

[Time axis: #1, #3, #2, #3, #1]
**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 $R = \frac{k}{n}$, 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

$k$ information bits

\[ \downarrow \]
Coding

\[ \downarrow \]

$n'$ coded bits

\[ \downarrow \]
Puncturing

$n$ transmitted bits
Incremental redundancy

CRC insertion, Turbo coding
Puncturing to
• generate different redundancy versions
• match the number of coded bits to the channel
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
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

Normalized System Throughput

Normalized Delay

Reduced hybrid ARQ round-trip delay

Fast Scheduling

Fast Link Adaptation

Normalized System Throughput
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

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FOR FURTHER INFORMATION...

Open the 3GPP specifications...

...or read The Book!
Available in English, Chinese, Korean and Japanese.