Radio Resource Management in 2G, 3G and 4G

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Readings

- [Holma]
- Ch 9 Radio Resource Management by Harri Holma, Klaus Pedersen, Jussi Reunanen, Janne Laakso and Oscar Salonaho
- Ch 10 Packet Scheduling by Jeroen Wigard, Harri Holma, Renaud Cuny, Nina Madsen, Frank Frederiksen and Martin Kristensson

Outline

- Introduction to RRM
- Power Control
- Handover Control
- Admission Control
- Congestion Control (Load Control)
- Packet Scheduling

What is a Radio Resource Unit?

RRU is “the set of physical transmission parameters necessary to support a signal waveform transporting end-user information corresponding to a reference services” [2].

FDMA (1G): Frequency bands
- TDMA (2G): Frequency bands & Time slots
- CDMA (3G): Frequency bands, Codes, and Power level
- OFDMA (4G): Radio resource block
Radio Resource Management (RRM)

- RRM mechanisms are needed for efficient utilization of air interface resources.
- RRM is required to:
  - Quality: Guarantee Quality of Service
  - Efficiency: Maximize the system efficiency
  - Coverage: Maintain the planned coverage area
  - Capacity: Provide high capacity

What are Tasks of RRM Mechanisms?

- Power control (PC)
  - Minimize power levels and provide adequate quality of signals
- Handover control (HC)
  - Handle the mobility of UEs across cell boundaries
- Admission control (AC)
  - Guarantee QoS and maximize system’s throughput by controlling an admission of a new call
- Congestion control (CC) or Load Control (LC)
  - Ensure that system is not overload, especially when RRM mechanisms work improperly
- Packet scheduling (PS)
  - Handle non real-time traffic (in 3G) and all traffic in 3.5G and 4G systems

Where is RRM performed in UMTS?

- Power control
- Fast power control
- Fast load control
- Outer loop power control
- Hardware control
- Packet scheduling
- Admission control
- Load control

Typical location of RRM algorithms in a WCDMA network
### Time Scales of RRM Mechanisms in UMTS

<table>
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<tr>
<th>RRM mechanism</th>
<th>Typical time scale between event and activation</th>
<th>Main function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner-loop Power control</td>
<td>1 slot (667 μs)</td>
<td>Control transmitted power level on a fast basis, 1500 MHz</td>
</tr>
<tr>
<td>Packet scheduling</td>
<td>1 frame (10 ms)</td>
<td>Control instantaneous bit rate especially for NRT data traffic</td>
</tr>
<tr>
<td>Admission control</td>
<td>Tenths to thousands of frames</td>
<td>Decide whether a new call will be accepted or rejected</td>
</tr>
<tr>
<td>Handover</td>
<td>Tenths to thousands of frames</td>
<td>Support the mobility of users</td>
</tr>
<tr>
<td>Congestion control</td>
<td>Tenths to thousands of frames</td>
<td>Maintain the congestion below the threshold and modify the network</td>
</tr>
</tbody>
</table>

**Time Scale of the different RRM mechanisms and their functions**

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**Where and when is RRM performed in LTE?**

- Majority of RRM functions are now performed in eNodeB (eNB)
  - Packet Scheduling
  - Admission Control
  - Handover
  - Link Adaptation
- **TTI = 1ms** means RRM have to be performed 1000 times/sec

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- Introduction
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- Handover Control
- Admission Control
- Congestion Control
- Packet Scheduling

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**Power Control**

- **General Power Control**
  - **Types of WCDMA Power Control**
    - Open-loop Power Control
    - Outer-loop Power Control
    - Fast-loop Power Control (Inner-loop Power Control)

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**WCDMA Power Control**

- **Purposes of power control**
  - Reduce interference in the system
  - Ensure that the receiver receives an adequate Signal level for its requirement
  - Mitigate the “near-far” problem in the uplink

The Received signal power levels at Node-B
(a) without power control (b) with power control

**WCDMA Open-loop Power Control**

A technique used to set the initial transmit power

**WCDMA Outer-Loop (slow) Power Control**

- Performed at 10-100 Hz. in both uplink and downlink.
  - RNC performs this PC in the uplink.
  - UE performs this PC in the downlink.

**Steps**

1. Estimates received signal quality (CRC, BER or BLER) after macro diversity combining in RNC.
2. Adjusts target SIR for a connection. (see flow chart)
   - If received signal quality > required quality, RNC informs Node-Bs to decrease the SIR target, otherwise the SIR target will be increased
3. The SIR target is sent to Node-Bs.
WCDMA Outer-loop Power Control (cont.)

Increase of $E_b/N_0$ target when the UE hits its maximum transmission power

WCDMA Fast Power Control (Inner-loop PC)

Main purpose is to combat effect of rapid changes in radio channels eg multipath fading.

- In the uplink direction, Node-B measures received SIR.
- If measured SIR < SIR target then TPC = 1 indicating UE must increase transmitted power (step size 1dB)
- If measured SIR > SIR target then TPC = 0 indicating UE must decrease transmitted power (step size -1dB)

At low UE speed, fast power control can compensate for fading of the channel and keep received power level fairly constant.

Power-rise is defined as ratio of average transmission power in a fading channel to that in a non-fading channel when the received power level is the same in both channels.
Why are handovers needed?

- **Call continuity** - to ensure a call can be maintained as an MS moves from the coverage area of one cell to another.
- **Call quality** - to ensure that if an MS moves into an area of poor quality or poor coverage, the call can be moved from the serving cell to a neighbouring cell (with better quality) without dropping the call.
- **Traffic Reasons** - to ensure that the traffic within the network is optimally distributed between the different layers or bands of a network.
4 Types of handover in GSM

- MS handover between different BS:
- Intra-system handovers:
  - 4 Types of handover in GSM
  - Basic Handover decision
  - WCDMA Handovers

Handover Causes in GSM

- Others causes:
  - Intelligent Underlay/Overlay (IUO)
  - Traffic Reason Handover (TRHO)
  - Direct Access to Desired Layer/Band (DADL/B)

WCDMA Handovers

- Intra-system handovers:
  - Intra-frequency handovers:
    - MS handover within one cell between different sectors:
    - Direct Access to Desired Layer/Band (DADL/B)
  - Soft Handover
  - Hard Handover

- Inter-system handovers:
  - Handover between WCDMA FDD and GSM900/1800: Hard
  - Handover between WCDMA FDD and TDD: Hard

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Softer and Soft handover

- MS in overlapping cell coverage area of two adjacent sectors of a BS.
- Communication between MS and BS is via two air interface channels (one for each separate sector).
- Different sectors have different scrambling codes.
- DL: MS tunes RAKE fingers to different sectors and combines outputs.
- UL: BS receives signals with different antennas, decodes and combines them.

Handover in LTE

- All handovers are hard handovers
- Two kinds of handover:
  - X2-based handover procedure:
    - Load balancing
    - Interference prevention
  - S1-based handover procedure:
    - Compatible with previous systems
    - No X2 interface between the two eNodeBs
    - source eNodeB has been configured
- Three phases:
  - Preparation phase
  - Execute phase
  - Complete phase

Active cells and soft handovers

CPICH Ec/Io (signal to interference plus noise ratio) as soft handover measurement quantity.
Active set: the cells in the active set form a soft handover connection to the UE.
Neighbour set/monitored set: list of cells that UE continuously measures, but pilot Ec/Io are not strong enough to be in active set.
The active set signalling causes load to the RNC.
Active set update depends on average mobility of users, cell size, network planning, etc.
Each finger in Rake receiver is tuned to one.

X2-based handover procedure and Phases

- Preparation Step 4 to 6
- Execution Step 7 to 9
- Completion After step 9

The key features of X2-handover for LTE handover are:
- Handover is performed between two eNodeBs only.
- Data forwarding may be operated per bearer.
- MME is only informed at end of handover procedure once the handover is successful.
- Release of resources at source side is triggered from target eNodeB.
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- Admission Control
- Congestion Control
- Packet Scheduling

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**WCDMA Admission Control**

- Admission control accepts or rejects a request establishment.
- Before admitting a new UE, admission control needs to check that the admittance will not sacrifice the planned coverage area or the quality of the existing connections.

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**WCDMA Power-based Admission Control**

In the interference-based admission control strategy, if the new UE is admitted by the uplink admission control algorithm, the total interference level is expected to be lower than the threshold value:

\[ I_{\text{total, old}} + \Delta I < I_{\text{threshold}} \]

This ensures that the interference level does not exceed the planned value.

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WCDMA Congestion Control (Load Control)

- Responsible for ensuring that the system is not overload and remains stable.
- Possible actions are:
  1. Downlink fast load control: Deny UE downlink power-up command
  2. Uplink fast load control: Reduce uplink Eb/No target used by uplink fast power control
  3. Reduce throughput of packet data traffic
  4. Handover to another WCDMA carrier
  5. Handover to GSM
  6. Decrease bit rate of real time UEs, e.g. AMR speech codec
  7. Drop low priority calls in a controlled fashion

Types of Congestion Control

1. Fast congestion control
   - Carried out in Node-B.
   - These actions can take place within one time slot, i.e. with 1.5 kHz frequency.
   - e.g. the downlink fast load control

2. Slow congestion control
   - Packet traffic reduced by packet scheduler

This phase intends to monitor the load of the system in order to trigger actions in the congestion resolution phase.

The normal parameter to be monitored is – in the uplink is the load factor – transmitted power in the downlink [2].

Congestion is detected in Node-B when, for example, the uplink load factor exceeds a given threshold for a certain period, 

- Period to detect congestion plays an important role
- Too long period may cause too many congestion resolution

This phase generally comprises three procedures [2]:

1. Prioritization: The quality of low priority connections will be degraded.
2. Load reduction: For example,
   a. Blocking new connections requesting admission
   b. Limit the transmission capability of certain connections
   c. Forcing a handover e.g. broad/frequency handover
3. Load check: If the load is below a certain threshold (e.g. for a certain period ATOR), then goal has been achieved.

This phase is to restore to the different mobiles the capabilities they had before the congestion was triggered.

Phase will continue until users affected by resolution mechanisms have received their transmission capabilities[2].

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Round Trip Time

The round trip time is defined as the delay of a small packet traveling from UE to a server and back

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WCDMA Packet Scheduling

The target of the scheduling is
(a) use efficiently (and fairly) any unused cell capacity for all non-real-time connections
(b) maintain interference levels within planned values, so real time connections are not affected.

The WCDMA packet scheduler, is located in RNC

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Packet Scheduling in LTE

- **A RRM mechanism that is responsible for:**
  - selection of users using a performance metric
  - transmit their packets such that all RB are fully utilized.
- **Single carrier wireless systems schedule one user at each scheduling slot.**
- **Multi-carrier wireless systems schedule multiple users at each scheduling slot.**
  - Users report their channel conditions (SNR) on each RB to serving eNodeB at each TTI
  - eNodeB select user with highest metric on each RB
  - A RB that is poor for one user may be a good RB for another.
  - This enabled multi-path fading effect to be exploited rather than combated in this system.

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Time-frequency Domain Scheduling

- **Performed at 1 ms interval (Transmit Time Interval, TTI).**
  - Consists of two time slots.
  - Two consecutive RRIs (in time domain) are available.

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LTE Packet Scheduling System Model

Well Known Packet Scheduling Algorithms

- Maximum Rate (Max-Rate).
- Round Robin (RR).
- Proportional Fair (PF).
- First-in-First-out (FIFO).
- Maximum-Largest Weighted Delay First (M-LWDF)
- Exponential/Proportional Fair (EXP/PF).

Maximum Rate (Max-Rate)

- Always selects the user with the highest achievable data rate.
  \[ k = \arg \max r_i(t) \]
  - Where \( r_i(t) \) is the achievable data rate of user \( i \) at time \( t \).
- Efficient utilization of the radio resources.
- Low in fairness for depriving users with poor channel conditions.

Round Robin

- Allocates equal share of transmission time to each user in a cyclic fashion.
- May have lower throughput performance compared to other algorithms for not taking advantage on channel-dependent scheduling.

Table II is used to map the computed SNR value to the associated maximum achievable data rate.

<table>
<thead>
<tr>
<th>Maximum SNR Level (dB)</th>
<th>Modulation and Coding</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>16QAM (2, 2)</td>
<td>166</td>
</tr>
<tr>
<td>1.7</td>
<td>QPSK (1, 2)</td>
<td>234</td>
</tr>
<tr>
<td>3.5</td>
<td>16QAM (3, 3)</td>
<td>448</td>
</tr>
<tr>
<td>6.5</td>
<td>16QAM (3, 3)</td>
<td>448</td>
</tr>
<tr>
<td>7.0</td>
<td>16QAM (3, 3)</td>
<td>672</td>
</tr>
</tbody>
</table>

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Proportional Fair (PF) Scheduling

- Aim to provide a balance between fairness and throughput.
- Selects a user whose metric \( k \) is highest.

\[
k = \arg \max \frac{r_i(t)}{R_i(t)}
\]

\[
R_i(t) = (1 - \frac{1}{t_c}) \times R_i(t-1) + \frac{1}{t_c} \times r_i(t-1)
\]

- \( r_i(t) \) is the achievable data rate of user \( i \) at time \( t \),
- \( R_i(t) \) is the average data rate of user \( i \) at time \( t \),
- \( t_c \) is the size of an update window,
- \( R_i(t-1) = 0 \) if user \( i \) is not selected for transmission at time \( t-1 \).

- The size of the update window enable PF to maximize throughput and satisfy fairness for each user.

Maximum-Weighted Largest Delay First (M-LWDF)

- Developed to support multimedia real time data users in a Code Division Multiple Access High Data Rate (CDMA-HDR).
- M-LWDF selects a user \( k \):

\[
k = \arg \max a_i W_i(t) \frac{r_i(t)}{R_i(t)}
\]

\[
a_i = \frac{(\log \delta_i)}{T_i}
\]

- where \( W_i(t) \) is the HOL packet delay of user \( i \) at time \( t \),
- \( T_i \) is the delay threshold of user \( i \) and,
- \( \delta_i \) is maximum probability for HOL packet delay of user \( i \) to exceed delay threshold of user \( i \).

- Has a relatively low Packet Loss Ratio (PLR) with a good throughput and fairness performance.

Exponential/Proportional Fair (EXP/PF)

- Developed to support multimedia application in an Adaptive Modulation and Coding and Time Division Multiplexing (AMC/TDM) system.
- The metric \( k \) is determined as below:

\[
k = \arg \max \left\{ \exp \left( \frac{\sum_{i \in RT} a_i W_i(t) - a_i W(t)}{1 + a_i W(t)} \right) \frac{r_i(t)}{R_i(t)} \right\}_{i \in RT}
\]

\[
\sum_{i \in RT} a_i W_i(t) = \frac{1}{N_{RT}} \sum_{i \in RT} a_i W_i(t)
\]

- where \( M(t) \) is the average number of RT packets at the serving eNodeB buffer at time \( t \),
- \( \epsilon \) and \( \kappa \) are constants,
- \( \tau_{\text{max}} \) is the maximum HOL packet delay of all RT service users and
- \( \tau_{\text{max}} \) is the maximum delay constraint out of RT service users.

Delay-Prioritized Scheduling Algorithm

- Designed to support loss-sensitive RT service in downlink LTE system.
  - Eg: video streaming service is very sensitive to packet loss.
- Approach: Prioritize users with HOL packet delay approaching delay deadline.

- Step 1: The algorithm selects user \( k \) as below:

\[
k = \arg \min d_i(t)
\]

\[
d_i(t) = T_i - W_i(t)
\]

- where \( T_i \) is the delay threshold of user \( i \) and
- \( W_i(t) \) is the HOL packet delay of user \( i \) at time \( t \).

- Step 2: Allocate the best available RB reported by the user.
Comparison of PS Algorithms

<table>
<thead>
<tr>
<th>Aspects</th>
<th>WCDMA</th>
<th>HSDPA</th>
<th>LTE</th>
</tr>
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<td>Function allocation</td>
<td>RNC</td>
<td>Node B</td>
<td>eNode B</td>
</tr>
<tr>
<td>Scheduling speed</td>
<td>TTI=1ms, High RRT and channel setup time consumption</td>
<td>TTI=1ms, Fast scheduling</td>
<td>TTI=1ms, Dynamic scheduling</td>
</tr>
<tr>
<td>Scheduling controller</td>
<td>MAC-e in RNC</td>
<td>MAC-e in Node B</td>
<td>MAC of Controller in eNode B</td>
</tr>
<tr>
<td>Scheduling mechanism</td>
<td>User-specific PS; Cell-specific PS;</td>
<td>Frequency/TIme based, OFDMA based;</td>
<td></td>
</tr>
<tr>
<td>Scheduling algorithms</td>
<td>Maintaining capacity for existing users while dividing remained capacity into new arrivals</td>
<td>Round Robin (RR) scheduler; Maxmin (CS scheduler); Proportional Fair (PF) algorithm; Request Activity Detection (RAD) scheduler and Proportional Fair scheduler (PFsch); OFDMA scheduling; Max-Max with 0/0/0 PF</td>
<td></td>
</tr>
</tbody>
</table>

Link Adaptation in Mobile Networks

Data Transmission in Radio Channels

- **Radio channel changes**
  - Typical Rayleigh channel varies 30dB
  - Very difficult to maintain reliable communication during deep fades
    - Quality of received signal cannot be guaranteed
    - BER target cannot be maintained
  - Systems are effectively designed for worst-case channel conditions.

Model of Link Adaptation

There are several parameters involved in radio transmission:

- Transmit power: Initial transmission power at the transmitter
- Received power: Received signal power
- Radio channel: multipath fading, shadowing, pathloss
- Noise and interference: AWGN and interference
- Modulation scheme: BPSK, QPSK, MQAM etc.
- Coding scheme: Turbo coding, Convolution coding etc
- Quality target: BER, maximum delay, jitter etc

Adaptable parameters:
- Transmit power
- Modulation/Coding scheme

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Link Adaptation

- There are two options to perform link adaptation:
  - 1. Power control
    - Keep received SNR near a desired (target) level
    - Constant data rate regardless of channel variations
      - Tx power may be increased by >20dB in deep fade
    - Desirable for circuit switched services such as voice calls
    - Use in CDMA system (WCDMA and cdma2000)
  - 2. Rate control (known as adaptive modulation and coding, AMC)
    - Keep transmit power at a constant level
    - Variable data rate depending on the channel qualities
      - No data transmission may occur during deep fade.
    - Desirable for delay-insensitive packet switched services
    - Used in modern wireless systems (EGPRS, HSDPA, LTE, WiMAX, and WiBro)

Feedback for Link Adaptation

- Power control: The transmitter needs to know how much power should be transmitted to combat the effect of channel fading so that the received SNR can be maintained.
- Rate control: The transmitter needs to know which modulation and coding scheme (MCS) should be assigned based on the instantaneous received SNR.

The receiver reports a massage via feedback channel so that the transmitter adjusts transmit power/MCS accordingly.

Link Adaptation in GPRS/EGPRS

- GPRS: CS 1-4, (Tradeoff of throughput vs. error performance)
  - Increase protection against errors
  - Increase achievable throughput

- EGPRS: MCS 1-9 (Introduction of 8PSK)
  - Increase achievable throughput

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**Link Adaptation in WCDMA**

- **Open loop power control**
  - Adjust the initial transmit power at the beginning of session
  - Use pilot signal to determine the transmit power

- **Outer loop power control**
  - Adjust target block error rate (BLER) as channel condition changes
  - Use error checking mechanism to adapt the BLER target
  - Performed in 10ms basis (100 Hz)

- **Inner loop power control**
  - Continuously adjust the transmit power to maintain target BLER
  - Use transmit power control (TPC) commands sent from the receiver

**AMC in HSDPA**

- AMC provides rapid variations in the transmitted bit rate on the HS-DSCH in response to the CQI reported from the UE
- Rel-99 1/3 rate Turbo Encoder is used
  - Rate Matching, Puncturing and Repetition are used to add more granularity, allowing an effective code rates between 1/4 and 3/4. See table below
- Imperfections in the CQI reporting can lead to inefficient AMC decisions so an “outer-loop” process based on the ACK/NACK can also be used to adjust the reported CQI
  - Inaccurate CQI reporting by UE (actual CQI algorithm not specified in 3GPP)
  - Time delay between CQI reporting and scheduling, particularly for fast moving UEs

<table>
<thead>
<tr>
<th>TFRC</th>
<th>Modulation</th>
<th>Code Rate</th>
<th>Mode Code</th>
<th>Maximum Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1/4</td>
<td>119 kbps</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>16-QAM</td>
<td>1/2</td>
<td>238 kbps</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>16-QAM</td>
<td>3/4</td>
<td>357 kbps</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>1</td>
<td>512 kbps</td>
<td></td>
</tr>
</tbody>
</table>

**Link Adaptation in LTE**

- LTE is operated in MIMO-OFDM system enabling link adaptation in frequency and spatial domains in addition to the time domain.
- LTE link adaptation works closely with packet scheduler

**Packet Scheduling**

- Time domain scheduling
- Frequency domain scheduling

**Link Adaptation**

- Outer loop link adaptation
- Inner loop link adaptation
- MIMO adaptation

**Inner loop link adaptation**

- Packet scheduler uses CQI to determine supportable MCS for a user depending on allocated RBs

**Outer loop link adaptation**

- Adjust the mapping between SNR and MCS using upper layer information such as NACK message
- Performed in similar manner as outer loop power control in WCDMA

**MIMO adaptation**

- Enable the use of multiple antenna configuration (MIMO)
- Requires extra feedback information such as Preceding matrix Indications (PMI) and Rank Indications (RI)