Radio Resource Management for OFDM Systems and Long Term Evolution (LTE) – Part II

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RRM: The Big Picture

Interference coordination

Scheduling

MIMO Control

Admission Control

Power control, Rate allocation

Mobility management, load balancing

D2D Communications
Intercell Interference Coordination for Evolved UTRA

UTRA = UMTS Terrestrial Radio Access Network
UMTS = Universal Mobile Telecommunication System
Background and Motivation

- **3GPP:**
  - Intercell Interference Coordination (ICIC)
  - Intercell Uplink Power Control: Overload Indicator
  - HO Measurement Reporting to support ICIC
  - 3GPP TS 36.213 E-UTRA Physical Layer Procedures

- **Research:**
  - Only a few papers assume multi-cell distributed non-full buffer scenarios
  - Interplay between PC+ICIC+Scheduling (for non-full buffer traffic) is not much studied (exceptions exist)
Point 1: The Two Cell Case

\[ C_{tot} = B \left( \log_2 \left( 1 + \frac{P_1 G_{11}}{N + P_2 G_{21}} \right) + \log_2 \left( 1 + \frac{P_2 G_{22}}{N + P_1 G_{12}} \right) \right) \]

⇒ Uncoordinated Reuse-1 is not always optimal

Point 2: The Multi-cell Cell Case

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum transmit power vector</td>
<td>( \left( \frac{3}{4}, \frac{3}{4}, \frac{3}{4}, 1, \frac{3}{2}, \frac{3}{4} \right) \times P_{tot} )</td>
<td>( (0,0,0,0,0,0) \times P_{tot} )</td>
<td>( \left( 0, \frac{3}{4}, \frac{3}{4}, \frac{1}{2}, 1 \right) \times P_{tot} )</td>
</tr>
<tr>
<td>Achievable data rate (Mbps)</td>
<td>12.78 (12.77-full power)</td>
<td>4.14 (1.92-full power)</td>
<td>7.71 (6.63-full power)</td>
</tr>
</tbody>
</table>

Uncoordinated Reuse-1 is typically (?) not optimal

Point 3: The Multi-cell Multi-User Cell Case

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Average number of users per cell</td>
<td>15</td>
</tr>
<tr>
<td>Users’ mean speed</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Handover</td>
<td>Hard handover</td>
</tr>
<tr>
<td>Multipath fading</td>
<td>3GPP SCM SuburbanMacro model</td>
</tr>
<tr>
<td>Link adaptation</td>
<td>ACM</td>
</tr>
<tr>
<td></td>
<td>Modulations: BPSK, QPSK, 16QAM, 64QAM</td>
</tr>
<tr>
<td></td>
<td>Code rates: 0.01-0.99</td>
</tr>
</tbody>
</table>
Point 3: The Multi-cell Multi-User Cell Case

<table>
<thead>
<tr>
<th></th>
<th>Scheduling attempts for exteriors</th>
<th>Scheduling attempts for interiors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round Robin</td>
<td>754</td>
<td>402</td>
</tr>
<tr>
<td>Proportional</td>
<td>665</td>
<td>455</td>
</tr>
</tbody>
</table>

⇒ ICIC Gain depends on the Scheduler
Impacts of “Collisions”

- Fewer user data bits can be carried in one PRB, as the link adaptation needs to select lower modulation order and/or lower coding rate to compensate the lower SINR.
- Fewer number of PRBs can be allocated to the UE in one subframe due to hitting the UE power limit (resulting in higher UE power consumption as well)
  - May have an impact on coverage
- More HARQ retransmissions may be needed for successful data delivery (due to BER degradation)
The collision compensation effect

- Throughput (and system capacity) depends on the \textit{effective number of bits carried per “occupied” PRB}
  - \( D_{\text{PRB-Coll}} ; D_{\text{PRB-NoColl}} \)

- Comparing this measure for the ICIC and No-ICIC cases
  - if \( 2*D_{\text{PRB-Coll}} \geq D_{\text{PRB-NoColl}} \) (2-cell case) holds then the throughput/capacity of the ICIC and No-ICIC cases are expected to be the same ("Compensation condition")

\[ \text{Cell-1 throughput} = D_{\text{PRB-NoColl}} \]

\[ \text{Cell-1 throughput} = 2*D_{\text{PRB-Coll}} \]
Dependence on the traffic model

- The assumptions on the traffic model have a key impact on what type of gains can be expected with ICIC
  - throughput (capacity), packet delay, transmission power, coverage
- In case of traffic types and scenarios where the “Compensation condition” holds, no throughput gains can be expected (gains in terms of delay and power can still be present)

Full buffer, peak rate limited (“CS”): There are throughput gains.

Non-full buffer, non-peak rate limited (“TCP”): There are Less/No throughput gains. “ICIC in time” may be useful.

Full buffer, non peak-rate limited: It results in continuous full-cell load (no difference between ICIC and No-ICIC)

Non-full buffer, peak rate limited: There is room for avoiding collisions (both in time and in frequency) ⇒ potential throughput gains. On the other hand, due to the compensation effect, gain may be small depending on e.g. load.

Narrow Band users, Full Buffer with Peak Rate Limitation, DL

ICIC for Reuse-1 system with offsets

The set of PRBs are divided into disjoint subsets and each cell gets assigned one of the subsets to be used for Exterior UEs \([n_1^{\text{(offset)}}, n_1^{\text{(offset)}} + N_i]\)

- the assignment can be done by planning and configured from O&M, or:
- negotiated between eNBs dynamically (self-configuration)

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3GPP R1-074444 “On Inter-cell Interference Coordination Schemes without/with Traffic Load Indication”, Ericsson.
3GPP R1-080359 “Further Considerations on the Use of Inter-Cell Interference Indication”, Ericsson.
Simulation Results
- (narrow band UEs) -

Largest gain at low or moderate load
up to 70% cell edge throughput gain
Geometry based algorithms perform the best
Random is almost as good as frequency-planned
ICIC - Conclusions

• ICIC without X2 communication yields gains for services with limited rate (PRB) requirement

• This gain is much dependent on traffic distribution, type of traffic and other factors

• For narrow band services, the ICIC potential (“near-optimum ICIC”) is significant
References

Admission Control

Idle Mode

RRC Connection Request

RRC Connection Setup

Connected Mode

Higher layer signaling (e.g. SIP)

SAE Access Bearer Request

Admission of a Radio Resource Control (RRC) Connection

Check the availability of radio resources, transport network resources and hardware resources before admitting new radio bearer or handover radio bearer.

• AC for GBR Services
• No AC for Non-GBR Services
1. Create Dedicated Bearer Request
   [QoS Info]
   From service layer (via PCRF, PDN GW and Serving GW, See 23.401)

   QoS Info (depending on service type):
   • Label (~ QoS Class Identifier)
   • GBR/MBR/AMBR
   • ARP
   • UL/DL Packet filters
   • … (FFS)

2. SAE Bearer Setup Request [S1: QoS Label, MBR/GBR/AMBR, ARP; + NAS (piggybacked): UL Filters]

3. RRC: SAE Radio Bearer Setup
   • Piggybacked NAS (containing UL filter)
   • Radio Bearer ID + associated parameters (ffs)

4. RRC: SAE Radio BS Response
   • Piggybacked NAS response

5. SAE Bearer Setup Response
   • Piggybacked NAS response

6. Create Dedicated Bearer Response

SAE Bearer Service Established

PHY Radio BS Establishment involves the evaluation and the reservation of the PHY radio resources.

RAC takes place upon a SAE Radio Bearer Setup Request
Intra-LTE Handover

- Network controlled HO
  - UTRAN decides when/where to make HO

- UE assisted HO
  - HO decision is based on UE measurements. UE measurement reporting is controlled by UTRAN

- Lossless HO
  - Source eNB uses packet forwarding to target eNB

- Late path switch
  - S1 connection is updated only when the HO has been completed
Intra-LTE Handover

**UE Measurements:**
- Reference Symbol Received Power (RSRP)
- Reference Symbol Received Quality (RSRQ)
- Carrier Received Signal Strength Indicator (RSSI)
- UE transmit power

Status info

Meas. report
Intra-LTE Handover

**Before HO**
- Mob. Management Entity (MME)
- S1 signaling

**HO Preparation**
- SAE GW
- X2 signaling connection
- When target cell fulfills the measurement reporting threshold, the UE sends the measurement report to (serving) eNB

**Radio HO**
- SAE GW
- X2 signaling connection
- Packet forwarding to ensure lossless HO

**Late Path Switch**
- SAE GW
CMC: Intra-LTE Cell Reselection

- **UE Measurements:**
  - Reference Symbol Received Power (RSRP)
  - Reference Symbol Received Quality (RSRQ)

- **Broadcast Information:**
  - Qqualmin
  - Qoffset_s,n

- Co-located carriers

- **eNB controlled cell reselection**

- **No eNB-eNB information exchange for cell reselection purposes**

<table>
<thead>
<tr>
<th>Carrier Frequency 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency 2</td>
</tr>
<tr>
<td>Carrier Frequency 3</td>
</tr>
<tr>
<td>Carrier Frequency 4</td>
</tr>
</tbody>
</table>
Proximity Based Applications

bump, http://bu.mp

Bump™ makes sharing with people as simple as bumping two phones together.


Whether you're looking for nearby events/parties or looking for happening places BuzzE can help you.

http://www.facebook.com/places

See where friends are. Discover new places.
Scenarios

Licensed spectrum
(D2D-dedicated or cellular, controlled interference)

Unlicensed spectrum
(unpredictable interference)

No network

Network assisted

Inter-operator roaming?
Some Design Questions

- Peer detection?
  - Prior D2D communication? During D2D communication?

- Mode selection?
  - Time scale? When to switch between D2D and NW? One shot or contiguous?

- Duplexing scheme, Scheduling, Power control, Hybrid ARQ?
  - NW control or distributed among D2D peers?

- NW schedules D2D traffic (~TTI level)
- NW allocates uni/bidirectional resource pool per D2D pair
  - Devices schedule traffic
- NW allocates common D2D resource pool
  - Devices schedule traffic

Interference Situation

- Choice of cellular resources for D2D impacts interference scenario
  - UL resources preferable – cellular access prioritized over D2D
  - DL resources ⇒ D2D interferes with cellular DL
  - UL resources ⇒ cellular UL interferes with D2D
Problem formulation

 › Multicell OFDM system;
 › Multiple cellular UEs and \textit{D2D candidates} per cell;
 › How to:
   - select mode (D2D vs cellular)
   - allocate resources (PRBs)
   - allocate transmit power.

UL resources ➔
-cellular UL interferes with D2D

\textbf{mode selection}
\textbf{scheduling}
\textbf{power control}
Mode Selection

- **Cellular (Relay) mode**
  - Mode: \( q = 0 \)
  - (orthogonal)
  - - in freq/time

- **Dedicated mode**
  - Mode: \( q = 1 \)
  - (orthogonal)
  - - in freq.

- **(UL) Reuse mode**
  - (non-orthogonal)
D2D Problem Formulation

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>Minimize sum power</td>
</tr>
<tr>
<td>Constraints C1</td>
<td>$x_{l,f}(q) = 0 \Rightarrow P_{l,f}(q) = 0$ otherwise $x_{l,f}(q) = 1 \Rightarrow P_{l,f}(q) \leq K$</td>
</tr>
<tr>
<td>Constraints C2</td>
<td>$x_{l,f}(q) = 1 \Rightarrow \gamma_{l,f}(q) \geq \gamma_{l,f}^{\text{tgt}}$</td>
</tr>
<tr>
<td>Constraints C3</td>
<td>No intra-cell interference for UEs/D2Ds in cellular mode</td>
</tr>
<tr>
<td>Constraints C4</td>
<td>Each user $l$ must be assigned at least $R_{l}^{\text{min}}$ PRBs</td>
</tr>
<tr>
<td>Constraints C5</td>
<td>Power allocation for user $l$ on PRB $f$ must guarantee a given $\gamma_{l,f}^{\text{tgt}}$</td>
</tr>
<tr>
<td>Constraints C6</td>
<td>Power allocation does not overwhelm a fixed power budget $P_{\text{max}}$</td>
</tr>
<tr>
<td>Constraints C7</td>
<td>Each user $l$ can exploit PRB $f$ employing at most one mode</td>
</tr>
<tr>
<td>Constraints C8</td>
<td>Cellular UE must adopt cellular mode</td>
</tr>
<tr>
<td>Constraints C9</td>
<td>Binary integer assignment</td>
</tr>
</tbody>
</table>

From the definition of SINR, constraints C2 involves

$$\gamma_{l,f}(q) = \frac{G_{h(l),f}(q)P_{l,f}(q)}{\sum_{j \neq l,q} G_{h(l),f}^j(q)P_{j,f}(q) + BN_0}$$

$$P_{l,f}(q) \geq \frac{\gamma_{l,f}^{\text{tgt}}}{G_{h(l),f}(q)} \left( \sum_{j \neq l,q} G_{h(l),f}^j(q)P_{j,f}(q) + BN_0 \right)$$

$$G_{h(l),f}(q)P_{l,f}(q) - \gamma_{l,f}^{\text{tgt}} \sum_{j \neq l,q} G_{h(l),f}^j(q)P_{j,f}(q) \geq \gamma_{l,f}^{\text{tgt}} BN_0 (1 - K(1 - x_{l,f}(q)))$$
Numerical Results: The Potential of D2D Mode

**Cellular Mode**

- Power tot. [W]

**D2D Mode**

- Power tot. [W]

**D2D Gain/Loss**

- Gain ≤ 99.8%
- Loss = 180%
Numerical Results: Impact of Mode Selection

Mode Selection vs Cellular Mode

Gain ≈ 99.7%

Gain ≈ 38%

Recall: Cell radius is 500m, max D2D dist = 1000m

M. Belleschi, G. Fodor and A. Abrardo, "Performance Analysis of a Distributed Resource Allocation Scheme for D2D Communications", IEEE Workshop on Machine-to-Machine Communications, Houston, TX, USA, December 2011.
Radio Resource Management for OFDM Systems and Long Term Evolution (LTE) – Part III

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Agenda

- Introduction
- The 3 MIMO explored: Diversity, Beam forming, Spatial Multiplexing
- The 4th MIMO: Multiuser MIMO

- MIMO in LTE
  - practical considerations

- The 5th MIMO: Multipoint Coordination
- Multimedia Broadcast/Multicast Services (MBMS) in LTE
Introduction
MIMO Scenarios

- Single Cell SISO
- Single Cell SIMO/MISO
- Single Cell SU MIMO
- Single Cell MU MIMO
- MU MIMO with IC Interference
- Cooperative Multi Cell MU MIMO
MIMO Advantages

- **Diversity gain**
  - Mitigates the effect of multipath fading
  - Transmits or receives over multiple antennas at which the fading is sufficiently de-correlated
  - Improves the statistics of instantaneous SNR in a fading channel;

- **Array gain (Power gain)**
  - Concentration of energy in one or more given directions (via precoding or beamforming)
  - Allows multiple users located in different directions to be served simultaneously (in MU MIMO);

- **Spatial multiplexing gain**
  - Transmission of multiple signal streams (to a single or multiple users (SDMA)) on multiple spatial layers by combinations of the available antennas.
MIMO - Diversity

- Full diversity: Each of the transmitted (e.g. QAM) symbols must be assigned to each of the transmit antennas at least once of the RBs (or symbol durations):
  - Space Frequency Block Coding
  - Space Time Block Coding

- Number of SISO links that can simultaneously be in the state of severe fading that the system can sustain:
  - \# Tr. Antennas x \# Rec. Antennas -1

- Fundamental tradeoffs:
  - between beamforming gain and cancelling interference
  - between multiplexing gain and diversity
MIMO – Beamforming

- The signals emitted by the different transmit antennas differ in phase and in amplitude (controlled by the weight associated with that antenna).
- The direction of the beam can thus be changed by changing the antenna weights (assuming fixed spacing between the antennas).

- Improves the SNR by transmitting energy into the user’s direction
- Mitigates inter-cell interference
- Applicable in low SNR scenarios (e.g. cell edge users)
- Improves coverage
MIMO – Spatial Multiplexing Gain

Spatial Multiplexing:

\[ r_{ch} > 1; \quad r_{tr} > 1 \]

A single data stream is “divided” (multiplexed) between multiple transmitting antennas and sent over separate spatial channels (but the same frequency).

- Lower SNR per stream than with a single stream (due to power constraint)
- Applicable in high SNR scenarios (e.g. cell center users)
- Improves peak rate
The 3 MIMO explored
MIMO Signal Model

Received signals on $M$ receive antennas: $\mathbf{R} = \mathbf{H} \mathbf{Y} + \mathbf{N}$

Channel rank: the number of simultaneously transmitted symbol streams that the MIMO channel can support
(~ number of independent modulation symbols per resource element)

Transmission rank: the number of actually transmitted streams
MIMO Signal Model (cont’d)

\[ R = HY + N \]

\[ X = (x_1, x_2, \ldots, x_P) \]

\[ X \rightarrow Y(X) \]

Spatial rate: \( P/T \)

1. \( y_1 \)
2. \( y_2 \)

\( h_{11} \)
\( h_{12} \)
\( h_{1M} \)
\( h_{21} \)
\( h_{22} \)
\( h_{2M} \)

\( r_1 \)
\( r_2 \)

\( h_1 \)
\( h_2 \)
\( h_M \)

\( y_1 \)
\( y_2 \)
\( y_N \)

\( h_{N1} \)
\( h_{N2} \)

\( h_{NM} \)

\( T \) is the number of time slots or number of OFDM subcarriers

may correspond to the data of one or possibly multiple users

\( T \) is the number of time slots or number of OFDM subcarriers

\( X \) is a group of \( P \) QAM symbols

\( Y(X) \) is a mapping function that maps the symbols to the signal
Alamouti Space-Frequency Code

Spatial Rate: 1

- no feedback from receiver to achieve full tr. diversity
- redundancy in space → no BW expansion
- low complexity decoder

Combining

\[
\begin{pmatrix}
    h_1^* & h_2 \\
    h_2 & -h_1
\end{pmatrix}
\]

Scaled version of input symbols

\[
s_1 = h_1^* r_1 + h_2 r_2^* = (|h_1|^2 + |h_2|^2) \cdot x_1
\]
\[
s_2 = h_2^* r_1 - h_1 r_2^* = (|h_1|^2 + |h_2|^2) \cdot x_2
\]
Beamforming with Single Antenna

- Receive beamforming for single stream $\mathbf{N}=1$, $\mathbf{M} > 1$
  - one symbol is transmitted per RB: $\mathbf{P/T}=1$ and $\mathbf{Y(X)} = \mathbf{X} = \mathbf{x}$
  - received signal vector: $\mathbf{R} = \mathbf{Hx} + \mathbf{N}$
  - received symbol after antenna combining: $\mathbf{z} = \mathbf{wR} = \mathbf{wHx} + \mathbf{wN}$
  - Beamforming vector: $\mathbf{w} = \mathbf{H}^H$

- Transmit beamforming for single stream $\mathbf{N} > 1$, $\mathbf{M} = 1$
  - one symbol is transmitted per RB: $\mathbf{P/T}=1$ and $\mathbf{Y(X)} = \mathbf{w} \mathbf{x}$
  - Beamforming vector: $\mathbf{w} = \frac{\mathbf{H}^H}{\|\mathbf{H}\|}$

  enforces a total power constraint
Receive Beamforming (MRC)

\[
\hat{x} = \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \cdot X + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \cdot \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} \cdot I + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \cdot \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}
\]
Spatial Mux without CSIT

- $M \geq N$; $N$ streams
  - Since the transmitter does not know the channel, there is no precoder:
    \[ Y(X) = \tilde{X} \]

- Receiver tries to recover stream $i (\tilde{x}_i, x_{i,2}, \ldots, x_{i,T})$:
  \[ w_i R = w_i H \tilde{X} + w_i N \]

- Receivers:
  - Zero Forcing
  - MRC
  - MMSE
  - SIC
  - MLD
Alamouti and Power Control

- performance of OPC and OPC + fairness in downlink OFDM-MIMO system
  - low rank transmission: Alamouti STBC + maximum ratio combining (MRC) receiver
  - higher rank transmission: SM + linear minimum mean square error (MMSE) receiver
  - adaptive modulation and coding scheme (MCS) selection
  - variable fairness constraints
  - modulation dependent channel information capacity calculation based on [8]

- performance comparison to equal power allocation (EPC)
- equal power allocation
  - does not require CSI
  - very low complexity

- question: are the gains of OPC worth obtaining accurate CSIT?

Notations

- $K$ OFDM-MIMO users, user $k$ employs $N_{R,k}$ receive antennas
- inter-cell interference (IF) is considered as Gaussian noise
- unified notations for the Alamouti and SM schemes
- SNR of user $k$ on subcarrier $n$ and stream $q$ given by

$$
\gamma_k^{n,q} \triangleq \left( \frac{|\{A_k^n\}_{(q,q)}|}{\sigma_{k,w}^{n,q}} \right)^2,
$$

where

$$
A_k^n = \text{Diag}\left( \sqrt{\frac{P_k^n}{N_T}} \|H_k^n\|_F^2 \right),
$$

$$
A_k^n = \text{Diag}\left( \sqrt{\frac{P_k^n}{N_T}} G_k^n H_k^n \right)
$$

for Alamouti and SM, resp.

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{k,w}^{n,q}$</td>
<td>variance of complex Gaussian IF and noise</td>
</tr>
<tr>
<td>$P_k^n$</td>
<td>tr. power allocated for user $k$ on subcarrier $n$</td>
</tr>
<tr>
<td>$N_T$</td>
<td>transmit antennas at the base station</td>
</tr>
<tr>
<td>$H_k^n$</td>
<td>channel matrix of user $k$ on subcarrier $n$</td>
</tr>
<tr>
<td>$G_k^n$</td>
<td>MMSE filter matrix of user $k$ on subcarrier $n$</td>
</tr>
</tbody>
</table>
Power Allocation Problem for Alamouti DL

- proposed nonlinear non-convex optimization problem

$$\max_{\mathbf{p}} \sum_{k=1}^{K} \sum_{n_k=1}^{N_k} \sum_{l_k=1}^{L_k} R_c^k (1 - \text{PER}^c(\{\mathbf{p}\}_k, M^c)) \text{LA}(\{\mathbf{p}\}_k, M^c)$$

subject to constraints:

$$\sum_{k=1}^{K} \sum_{n=1}^{N_k} P^n_k \leq P_T,$$

$$P^n_k \geq 0, \forall k, \forall n,$$

$$T_k \leq F \cdot T_l, \forall k, \forall l \ (1)$$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$N_k$</td>
<td>subcarriers of user $k$</td>
</tr>
<tr>
<td>$L_k$</td>
<td>data streams of user $k$</td>
</tr>
<tr>
<td>$R_c^k$</td>
<td>coding rate of user $k$ on subcarrier $n$</td>
</tr>
<tr>
<td>$\text{PER}^c$</td>
<td>packet error rate on $c = {k, n, q}$</td>
</tr>
<tr>
<td>$\text{LA}(\cdot)$</td>
<td>link adaptation (LA) function</td>
</tr>
<tr>
<td>${\mathbf{p}}_k$</td>
<td>${\mathbf{p}}_k = {P^1_k, \ldots, P^{N_k}_k}$</td>
</tr>
<tr>
<td>$M^c$</td>
<td>M-QAM mod. on $c = {k, n, q}$</td>
</tr>
<tr>
<td>$P_T$</td>
<td>total transmission power of the base station</td>
</tr>
<tr>
<td>$T_k$</td>
<td>throughput of user $k$</td>
</tr>
<tr>
<td>$F$</td>
<td>fairness coefficient</td>
</tr>
</tbody>
</table>
Alamouti and Power Control

SM OPC yields superior throughput, except high unbalance + low power

gain of SM OPC+fairness to SM EPC is not significant

SM EPC is better, but no guaranteed fairness

(i) Throughput of Alamouti STBC and SM when OPC and EPC are applied together with adaptive MCS

(j) Throughput of SM EPC, adaptive MCS and SM OPC+fairness, adaptive MCS

Optimal MIMO Transmission

- Would like to transmit T symbols in each stream:
  Stream/Layer – i : Symbols: \([x_{i,1}, x_{i,2}, \ldots, x_{i,T}]\);

- Each stream may adopt a distinct code rate and modulation:

\[
\begin{align*}
X & \rightarrow Y(X) \\
\bar{X} &= \begin{pmatrix}
  x_{1,1} & x_{1,2} & \cdots & x_{1,T} \\
  \vdots & \vdots & \ddots & \vdots \\
  x_{N,1} & x_{N,2} & \cdots & x_{N,T}
\end{pmatrix}
\end{align*}
\]

\[
Y(X) = VP\bar{X}
\]

- SVD of the channel:
  \[
  H = U\Sigma V^H
  \]

  – \(i^{th}\) column of \(V\) : \(i^{th}\) right singular vector of \(H\)
  – \(i^{th}\) row of \(U^H\) : \(i^{th}\) left singular vector of \(H\)

\[
U_i^H R = \lambda_i \sqrt{p_i} [x_{i,1}, x_{i,2}, \ldots, x_{i,T}] + U_i^H N
\]

\(\lambda_i\) is the \(i^{th}\) singular value of \(H\)

receive beamforming vector for the \(i\)-th stream
The 4th MIMO: Multiuser MIMO
Single User and Multi User MIMO

- All spatial dimensions assigned to **one** user.
- Separation of users by TDMA, FDMA.

\[ R = HY + N \]

- Spatial dimensions assigned to **several** users.
- Separation of users by TDMA, FDMA and SDMA.

\[ R = HY + N \]

**multiple users over the same RB**

.single antenna UE**

\[ \text{DL: transmit BF} \]
\[ \text{UL: receive BF} \]

**separation and de-correlation**
Potential of MU MIMO

- Limited exploitation of multi-user diversity.
- Number of spatial dimensions is limited by number of antennas at UE.
  ⇒ Potential spatial dimensions are wasted if UEs have less antennas than node B.
- Used spatial dimensions may be weak in case of low rank channel (spatial correlation).

- Better exploitation of multi-user diversity.
- Full number of spatial dimensions which is supported by node B can be exploited.
  ⇒ Capacity gain if UEs have less antennas than node B.
- Stronger spatial dimensions are exploited, particularly in case of low rank channel.

Design goals:
- Precoder for spatial user separation
- Scheduler for exploitation of multi-user diversity
Uplink vs Downlink MU MIMO

Uplink MU-MIMO
- Optional CSIT
- CSIR Channel state info at Rx
  \[ Y(X) = \bar{X} \]
- Multiple antenna UEs: space-time coding
  - All Rx antennas can cooperate.
  - Tx antennas of different users cannot cooperate.
    - Inter-user interference can be resolved at Rx.
    - Same detection methods as in SU-MIMO can be applied.
  - Transmit power constraint per user.

Downlink MU-MIMO
- CSIT Channel state info at Tx
- Transmit beamforming
- Multiple antenna UEs: MRC,...
  - All Tx antennas can cooperate.
  - Rx antennas of different users cannot cooperate.
    - Inter-user interference needs to be resolved at Tx.
  - Sum transmit power constraint.

Main challenge: Scheduling

Main challenges:
- Precoding for user separation
- Scheduling
SU MIMO and MU MIMO

<table>
<thead>
<tr>
<th>SU-MIMO</th>
<th>MU-MIMO</th>
</tr>
</thead>
</table>
| • high user throughput  
• high peak data rates | • high system capacity  
• full exploitation of multiuser diversity |
| | • degradation of peak data rates due to MU interference (ZF is not working perfectly due to imperfect CSIT) |
| | • multiple transmit antennas are not fully exploited  
• multiuser diversity is not fully exploited |

**DL MU MIMO:** relies on CSIT and smart scheduling

**UL MU MIMO:**
- sufficiently many antennas are needed at the eNB to reject interference
  - spatial separability of simultaneously scheduled users
MIMO in LTE
MIMO - Practical Considerations

- Propagation environment and antenna spacing affects antenna correlation and the MIMO channel
  - in LOS situations strong correlation between spatial signatures $\rightarrow$ limiting the gain of SM
  - orthogonal polarization of antennas may help
  - also in diversity oriented schemes, the matrix elements should be decorrelated

- Channel coefficient estimations
  - reference signal design
  - limited CSIT affects transmit beamforming

- DL MU MIMO: relies on CSIT at eNB and smart scheduling

- UL MU MIMO: CSIR and pairing are critical + sufficiently many antennas are needed at the eNB to reject interference
  - spatial separability of simultaneously scheduled users
MIMO in LTE

LTE CL-MIMO supports maximum 2 codewords (CW)

Rank 1
2 Tx
CW1 → Layer 1 → Precoder

Rank 2
CW1 → Layer 1
CW2 → Layer 2

Rank 1
4 Tx
CW1 → Layer 1 → Precoder

Rank 2
CW1 → Layer 1
CW2 → Layer 2

Allowed only in retransmission

Rank 3
CW1 → Layer 1
CW2 → S/P → Layer 2 → Layer 3

Rank 4
CW1 → S/P → Layer 1
CW2 → S/P → Layer 2 → Layer 3 → Layer 4

Precoder
Transmit Diversity Schemes

- Transmit diversity is defined for 2 or 4 transmit antennas and one data stream (one codeword);

- Advantageous for channels for which no uplink feedback signaling is available (e.g. MBMS, PBCH, synch signals);

- Advantageous in low SNR situations the PDSCH can also be configured in transmit diversity mode.
DL Rank-1 Beamforming

- eNB tries to direct the beam towards the UE direction (DoA)
- UE is not aware of receiving a directional transmission
- Applied to PDSCH (cell range may still be limited by control channels)
SU MIMO in LTE

- Rank adaptation
- Spatial multiplexing
- Precoding

# codewords ≤ # layers ≤ # antenna ports

<table>
<thead>
<tr>
<th>feedback</th>
<th>2 Tx</th>
<th>4 Tx</th>
</tr>
</thead>
<tbody>
<tr>
<td>rank indicator (RI):</td>
<td>1 bit</td>
<td>2 bit</td>
</tr>
<tr>
<td>precoder matrix indicator (PMI)</td>
<td>2 bit</td>
<td>4 bit</td>
</tr>
<tr>
<td>channel quality indicator (CQI)</td>
<td>1st codeword: 4 bit&lt;br&gt;(modulation and coding scheme (MCS))&lt;br&gt;2nd codeword: 3 bit (differential)</td>
<td></td>
</tr>
<tr>
<td>channel quality indicator (CQI)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1-2 codewords

QPSK
16 QAM
64 QAM

1-4 layers

2 or 4 Tx antennas

Layer 1
Layer 2
Layer 3

same or different code words

layer: spatial dimension = # MIMO streams
rank: number of layers
codeword: encoded data block (MAC)
The 5th MIMO
Coordinated Multipoint Transmission

- Data is available at each BS
- Data transmitted from multiple points at a time

- Data is only available at serving cell but user scheduling/BF decisions are made with coordination among cells

Joint processing -> coherent combining

Packet sharing

Joint beamforming and scheduling

Coordination on scheduling

Simultaneous reception

UL signal is received at multiple points
Cooperative Multipoint (CoMP) Systems

- CoMP systems support the exchange of:
  - control information ("3GPP X2")
  - channel state information
  - user data

- Multipoint coordination is a means to provide higher spectral efficiency:
  - Joint radio resource management (scheduling and power control)
  - Joint signal processing (MMSE, SIC,...)
  - Both...

- Question: How should radio resource management and signal processing work in concert such that:
  - Capacity is maximized subject to power budget OR:
  - Sum power is minimized subject to capacity target?
Virtual BS-\(k\): A cluster of base stations that cooperate in the reception of User-\(k\).

Each user is associated with a single virtual base station.

**Solution:**
Channel dependent "opportunistic" SINR-target setting as a means of power control in Network MIMO systems. Advanced numerical optimization technique to find the operating point.

**Conclusion:**
Optimal SINR target setting can reduce the sum power or increase the sum rate in network MIMO systems.

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Multimedia Multicast/Broadcast Service (MBMS)
Multimedia Broadcast Multicast Service (MBMS)

**Dedicated Cell Scenario**
- Cell resources are dedicated to provide MBMS service
- Cell typically becomes part of a Single Frequency Network
  - eNBs send identical info/RB
  - seen as single transmission by the UE (no HO needed)
  - Cell can dynamically join/leave an SFN
- Multicast Channel (MCH)
  - no hybrid ARQ

**Mixed Cell Scenario**
- Unicast and Broadcast/Multicast Services in the same cell
- Single Cell Transmission: Make use of DL shared channel
- Multicell Transmission: Cells form an SFN
  - Cell can dynamically join/leave an SFN
  - MCH time multiplexed with other LTE channels
Mixed Multicell Cell Scenario
- Multicell Transmission: Cells form an SFN
  - Cell can dynamically join/leave an SFN
  - MCH time multiplexed with other channels

Single Frequency Networks
- Same signal on same physical resource
- No (soft/selective) combining: no impact on UE

Resource Management
- Central coordinating function to coordinate resource allocation within the SFN area and to handle resource bottleneck in the SFN overlapping area
- ICIC between MBSFN and other areas
MBMS Architecture

SFN transmission: accurate synch is needed (e.g. GPS)
Single cell transmission: scheduling and power allocation

Summary

- OFDM and OFDMA provide a means to manage time, frequency, power (and space) resources with fine granularity.

- 3GPP LTE integrates these concepts into a world-wide standard.

- Current research targets further optimization and even higher performance (towards LTE Advanced).