Smart Scheduler
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>3</td>
</tr>
<tr>
<td>2. Smart Scheduler features and benefits</td>
<td>3</td>
</tr>
<tr>
<td>3. Smart Scheduler with explicit multi-cell coordination</td>
<td>9</td>
</tr>
<tr>
<td>3.1 Distributed RAN with X2 and non-ideal backhaul</td>
<td>10</td>
</tr>
<tr>
<td>3.2 Centralized RAN</td>
<td>11</td>
</tr>
<tr>
<td>3.3 Enhanced Inter-Cell Interference Control (elICIC) with co-channel small cells</td>
<td>12</td>
</tr>
<tr>
<td>4. Further evolution of LTE scheduling</td>
<td>13</td>
</tr>
<tr>
<td>5. Summary</td>
<td>14</td>
</tr>
<tr>
<td>6. Abbreviations</td>
<td>15</td>
</tr>
</tbody>
</table>
1. Introduction

With more than 500 million LTE subscribers as of early 2015, LTE has become the fastest adopted mobile broadband technology and is about to evolve for the connectivity needs of the programmable world, for serving human users as well as the Internet of Things. LTE in FDD and TDD mode (TD-LTE) is designed to work with all the cells using the same frequency, a so-called frequency reuse of one. This provides the highest network efficiency and enables high data rates close to the base station. The main drawback with frequency reuse of one is the high interference experienced when the terminal is between two cells.

Boosting cell edge performance is the main purpose of Smart Scheduler. It also enhances the average data rate and system capacity by taking signal fading and interference during packet scheduling into account. Smart Scheduler algorithms, benefits, the effect on the network architecture and further evolution are discussed in this white paper. If not otherwise explicitly stated, all statements are valid for both LTE (in FDD mode) as well as for TD-LTE.

![Diagram of Frequency Reuse](networks.nokia.com)

Figure 1. Frequency reuse of one creates high inter-cell interference

2. Smart Scheduler features and benefits

Although LTE radio technology is highly standardized by 3GPP, this standardization applies only to the interfaces. Aspects such as the network algorithms, including link adaptation, power control and packet scheduling are not standardized. This raises the possibility of varying performance among networks, due to the different algorithms used among vendors. The most relevant features and benefits are described in this section. Packet scheduling can make use of different sources of information to allocate resources and coordinate activities to avoid interference.
These information sources are:

- Channel Quality Information (CQI) from terminal to base station for downlink scheduling
- Sounding Reference Signal (SRS) measurements and interference measurements in the frequency domain for uplink scheduling
- Load and other information exchange over the X2 interface between base stations. Under Release 8, the X2 interface allows some exchange of information between base stations, but further extensions will be discussed in 3GPP and can also be added as a proprietary solution
- Quality of Service (QoS) parameters from the packet core network

Figure 2 shows these different input information options.

Smart Scheduler can use these different input values to optimize packet scheduling and link adaptation and LTE allows considerable freedom to define allocations in the time, frequency and power domains. Although a number of different features are required for the different use cases, the same features are used both in Frequency Division Duplex (FDD) and Time Division Duplex (TDD) based LTE. Smart Scheduler uses the following main features:

- Frequency Selective Scheduling (FSS). This improves network performance in the event of frequency selective fading and fractional inter-cell interference. FSS consists of Channel Aware Scheduling (CAS) and Interference Aware Scheduling (IAS). Field measurements show that FSS can improve cell edge data rates by more than 30%.
- Interference shaping can be used to improve the efficiency of the inter-cell interference avoidance. When cell loading is low, the number and set of physical resource blocks is adapted only slowly according to traffic fluctuations. This approach helps adjacent highly loaded cells to avoid inter-cell interference more efficiently, based on UE CQI reporting. Studies show gains exceeding 100%.
- QoS differentiation improves cell edge performance by allocating more resources for users in weak channel conditions. QoS can be used to maintain the data rate, for example for video streaming services. Using operator specific

Figure 2. Input information for coordinating resource usage
QoS Class Identifier (QCI) values gives even more flexibility. The minimum guaranteed cell edge data rate can also be obtained by a Nominal Bit Rate (NBR) which works even without QoS classes with guaranteed bit rates. Cell edge prioritization has only a minor effect on the cell aggregate throughput capacity. Typically, cell edge throughput improvement of 30% can be obtained at the cost of 5% cell throughput capacity. The capacity measured in the number of satisfied subscribers is higher.

- Uplink power control with interference awareness takes into account adjacent cells when allocating the uplink transmission power. The feature minimizes inter-cell interference and helps to boost uplink data rates.
- Intra-frequency load balancing helps when the load in the adjacent cells is not balanced. The idea is to modify handover parameters based on the information exchange of the X2 interface. If there are double the number of users in the adjacent cell, the intra-frequency load balancing can improve the cell edge data rate by 30%.
- Multi-cell scheduling can reduce the power levels (muting or related variants) in adjacent cells to minimize interference, allocating different times and frequencies among the cells. It selects users and power levels in multiple cells to combine the benefits of frequency-selective scheduling and spectral efficiency gain due to reduced interference. The coordination happens between the sectors of one base station, or over the X2 interface between the base stations. Multi-cell scheduling can improve cell edge performance by 20%. TD-LTE base stations need to be synchronized while the synchronization of LTE FDD base stations is not mandatory and is typically not used by operators for FDD deployments. Note also that in a synchronized network the reference signals overlap in adjacent cells. Therefore, terminals should preferably support cancellation of common reference signals for better performance.

Figures 3 and 4 show the Smart Scheduler use cases, features and gains. Figure 4 shows the gains of the individual scheduling functionalities when used jointly. More gain can be obtained in HetNet scenarios with eICIC.

<table>
<thead>
<tr>
<th>Use case</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional inter-cell interference</td>
<td>Multi-cell scheduling</td>
</tr>
<tr>
<td>Unbalanced loading between cells</td>
<td>Intra- and inter-frequency load balancing</td>
</tr>
<tr>
<td>HetNet</td>
<td>eICIC</td>
</tr>
<tr>
<td>Minimum cell edge rate required</td>
<td>QoS differentiation and nominal bit rate</td>
</tr>
<tr>
<td>Fractional inter-cell interference</td>
<td>FSS including Interference Aware Scheduling (IAS) and Channel Aware Scheduling (CAS)</td>
</tr>
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<td>Frequency selective fading</td>
<td>Baseline scheduler</td>
</tr>
</tbody>
</table>

Figure 3. Smart Scheduler use cases and solutions
Frequency Selective Scheduling (FSS) is the most important part of Smart Scheduler. The multipath propagation in the mobile environment makes the fading frequency selective. The typical coherence bandwidth of the macro cell channel is 1-2 MHz, meaning there are both faded and non-faded frequencies in a single LTE carrier. LTE radio uses Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink. Therefore, FSS allows use of those parts of the carrier (called Physical Resource Blocks) not faded for the transmission. The concept is illustrated in Figure 5. Information about channel fading can be obtained from terminal CQI reports in the downlink and from SRS in the uplink.

Figure 4. Smart Scheduler downlink data rate gains with non-ideal backhaul

Figure 5. Frequency Selective Scheduling to minimize fading impact
FSS can also be used to avoid inter-cell interference. An example is shown in Figure 6 where the interfering cell is partially loaded. The terminal is connected to the target cell but receives strong interference from the adjacent interfering cell.

The terminal reports sub-banded CQI values in the frequency domain to the target cell. Low CQI values are reported on those sub-bands where the interfering cell is currently transmitting, while high CQI values are reported in other sub-bands. The target cell with FSS tends to allocate blocks of downlink physical resource to the terminal with the lowest interference. The other resource blocks in the target cell can be allocated to other terminals not suffering interference from the adjacent cell.

The benefits of FSS include:

- Effective inter-cell interference coordination without explicit inter-base station coordination
- Use of terminal CQI reports for interference mitigation, without coordination signaling between the base stations
- Improved cell edge data rates, as well as better total cell capacity.

As part of the Smart Scheduler concept, the underlying link adaptation function is critical for the success of features such as FSS. The quality of reporting from each active terminal is constantly monitored and adjusted to help achieve better scheduler decisions. Using these methods, Nokia has
shown the practical value of FSS in numerous commercial LTE networks. Figure 7 shows an example field measurement result with 10 MHz bandwidth.

Interference shaping, as illustrated in Figure 8, further improves the efficiency of FSS’s inter-cell interference avoidance. When the cell loading is low, the number and set of physical resource blocks is adapted only slowly according to traffic fluctuations. This approach makes it more efficient for adjacent high loaded cells to use terminal CQI reporting to avoid inter-cell interference. Figure 9 illustrates example field measurement results with FSS and with interference shaping. The combined gain is 60%. High gains can be achieved in the distributed solution with cleverer scheduling without any fast signaling over the X2 connection and without any centralized network element.

Figure 7. Field measurements with Frequency Selective Scheduling (FSS) in downlink.

Figure 8. Interference shaping for more efficient interference avoidance.
3. **Smart Scheduler with explicit multi-cell coordination**

Performance can be improved still further by coordinating the allocation of resources in adjacent base stations and by using Release 11 capable terminals having enhanced inter-cell interference reporting capabilities. Figure 10 shows the network architecture options for supporting multi-cell scheduling.

Option a) with distributed RAN is the most common solution today. 3GPP specifications in Release 12 further enhanced inter-cell interference coordination over X2 interfaces. Option b) is Centralized RAN where the baseband processing is placed in the centralized location. A third option with a new network element

![Diagram showing network architecture options for explicit multi-cell scheduling](image)

**Figure 10. Network architecture options for explicit multi-cell scheduling**
for the interference control was considered in the studies but 3GPP decided that no new interfaces will be defined for the new network element.

3.1 Distributed RAN with X2 and non-ideal backhaul

Today’s typical LTE architecture, shown in Figure 10a, features a non-ideal backhaul with either microwave radio, IP connected fiber or copper based transport. Multi-cell scheduling needs to coordinate the use of resources in adjacent base stations over non-ideal backhaul, while making full use of FSS gains in fast scheduling. The coordination between cells of different base stations uses the X2 interface.

Each scheduler that requests coordination from its neighboring base stations to aid a user at the cell edge can still take into account FSS gains for that user. This means that FSS gains can be preserved while also adding the gains from multi-cell coordination. The evolution from fully distributed architecture to multi-cell coordination over X2 is a straightforward software upgrade – no new network elements or interfaces are needed. Note that fast local coordination can be implemented between the cells in one base station without inter-base station coordination.

The gain from multi-cell coordination is illustrated in Figure 11 as a function of X2 latency. Dynamic Point Selection algorithm is utilized in the studies to enable fast switching of the data transmission between the different cells. Dynamic Point Selection is one implementation of Coordinated Multipoint Transmission (CoMP) over non-ideal backhaul. The results indicate that multi-cell coordination can provide major gains for the cell edge data rates when X2 latency can be minimized. The latency preferably should be below 5 millisecond to bring clear gains over intra-site coordination only.

![Gain of Dynamic Point Selection](image)

**Figure 11.** Gain of multi-cell coordination with distributed architecture as a function of X2 latency
3.2 Centralized RAN

The final multi-cell architecture shown in Figure 10b is centralized scheduling in the baseband pool. This is the architecture used for a network with ideal transport. The baseband pool requires a low latency direct dark fiber connection between the RF heads and the baseband pool. The baseband pool is also referred to as Centralized Radio Access Network.

Centralized RAN is like a super-sized base station. It enables the most advanced multi-cell coordination because all the functionalities are in the same location: link adaptation, power control, fast FSS and multi-cell coordination. Centralized RAN architecture also enables Joint Transmission and Joint Reception Coordinated Multipoint (CoMP) between different sites, while intra-site CoMP can also be implemented in the distributed RAN architecture.

CoMP functionality is defined in 3GPP Release 11 but uplink CoMP can be implemented with legacy Release 8 terminals, although the downlink CoMP requires Release 11 terminals. Uplink CoMP also gives more gain, while downlink CoMP gains are limited. An excellent use for Centralized RAN is to boost capacity in stadiums and other mass event locations. These events tend to be uplink limited because many people want to send pictures from the event.

In the traditional solution, the terminal transmission is received by a single cell, while in this scheme the same terminal transmission can be received by multiple cells and combined in the baseband module. The inter-cell interference turns into a constructive signal. The solution is illustrated in Figure 12. The installation of fiber between baseband modules and RF is relatively simple in these event areas.

The Nokia Flexi Multiradio Base Station enables CoMP by providing fast interconnections between the baseband modules. Nokia Centralized RAN has been proven in commercial networks in large stadiums, with practical gains exceeding 100%.
The gains from Nokia Centralized RAN in live networks are shown in Figure 13. The comparison can be obtained by switching Centralized RAN feature off and on during the mass event. The gains in the mass events are typically at least 100-200%.

3.3 Enhanced Inter-Cell Interference Control (eICIC) with co-channel small cells

Small cells are an attractive solution for boosting hot spot capacity and coverage. Interference management needs to be considered when small cells are deployed on the same frequency as macro cells.

3GPP Release 10 offers a way to manage the interference in the time domain. This solution is called enhanced Inter-Cell Interference Coordination (eICIC) and is shown in Figure 14. The macro cell leaves some empty sub-frames called Almost Blank Subframes (ABS). During these sub-frames, the small cell can serve terminals that would otherwise receive too much co-channel interference from the macro cell.

The main advantage of eICIC comes when several small cells can benefit from macro cell empty subframes. eICIC performance is further boosted in Release 11 by using terminal interference cancellation to minimize inter-cell interference, which is known as further enhanced ICIC (feICIC). Optimized eICIC requires that the number of ABS frames and the handover parameters are adjusted to take account of current traffic conditions and terminal locations. The semi-static solution is a slow approach, modifying the feICIC parameters over several seconds. The fast feICIC method adapts quickly to the number of ABS sub-frames, reallocating resources between macro cells and small cells depending on current requirements. Nokia’s unique algorithm is based on the fast adaptation of ABS-blanking and cell range extension for maximum benefit from small cell deployments. Figure 15 shows the throughput gains, with dynamic eICIC nearly doubling user throughputs in HetNets.
Nokia eICIC brings benefits also for the legacy devices without Release 11 feICIC support. That capability is important for the practical networks since feICIC terminal penetration is still low. Nokia solution is based on the advanced link adaptation algorithms.

Nokia’s customer SK Telecom in Korea was the world’s first operator to commercialize eICIC.

4. Further evolution of LTE scheduling

3GPP has defined Inter-site carrier aggregation in Release 12. The feature allows the terminal to receive data simultaneously from both the macro cell and from the small cell and the two cells need no fiber backhaul. Even wireless backhaul with some delay is acceptable. The X2 interface is used between the macro cell and small cell to coordinate schedules. The macro cell and the small
Inter-site carrier aggregation uses Dual Connectivity where the terminal has simultaneous radio connection to both macro and small cell, offering reliable mobility.

3GPP has also defined a solution where terminals can cancel the inter-cell interference by obtaining assistance from the network. This feature is called Network Assisted Interference Cancellation and Suppression (NAICS) and is part of Release 12. If terminals can cancel interference, it may be more efficient to use all resources in co-channel cells instead of muting resources. The multi-cell scheduling and muting algorithms need to be flexible enough to benefit from the advanced capabilities of future terminals.

5. Summary

While LTE has been highly standardized by 3GPP, the network algorithms including packet scheduling are not standardized. The packet scheduling in LTE has the freedom to control the allocation of resources in time, frequency and power domains.

Smart Scheduler can improve cell edge data rates by more than 100% in the presence of inter-cell interference compared to baseline wideband scheduling, and improve the cell capacity by more than 20%. The main component of Smart Scheduler is frequency selective scheduling, which avoids fading and interference in the frequency domain, combined with Quality of Service differentiation and intra-frequency load balancing. Nokia’s innovation – Interference Shaping – increases the cell edge throughput further by up to 100% when the cell loading is unbalanced.

Additional cell edge gains can be obtained by multi-cell scheduling, a simple software upgrade to distributed base stations. Scheduling information is shared between base stations over the X2 interface.
The most advanced multi-cell coordination can be obtained with baseband pooling in a Centralized RAN. The baseband pool deployment assumes a direct fiber connection between baseband and RF sites. Centralized RAN provides the biggest benefits in uplink capacity, which is especially useful in high capacity events. The efficiency of small cell deployment can be boosted by using a dynamic eICIC configuration to manage the interference between macro cells and small cells.

6. Abbreviations

3GPP  Third Generation Partnership Project
BTS  Base station
CAS  Channel Aware Scheduling
CLPC  Closed Loop Power Control
CoMP  Coordinated Multipoint
CQI  Channel Quality Information
C-RAN  Centralized Radio Access Network
eCoMP  Enhanced CoMP
eICIC  Enhanced Inter-Cell Interference Coordination
FDD  Frequency Division Duplex
FSS  Frequency Selective Scheduling
IAS  Interference Aware Scheduling
OFDMA  Orthogonal Frequency Division Multiple Access
OLPC  Open Loop Power Control
QoS  Quality of Service
RRH  Remote Radio Head
SC-FDMA  Single Carrier Frequency Division Multiple Access
SRS  Sounding Reference Signal
UE  User Equipment, terminal

References

- 3GPP TR 36.874: Coordinated multi-point operation for LTE with non-ideal backhaul
- SK Telecom: SK Telecom and Nokia Networks Announce World’s First Commercialization of eICIC