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State of Art and Expected Evolution of Smart Scheduling Techniques in LTE

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Key Study Question:

"Based on vendor inputs on the commercial availability and benefits of smart scheduling will operators be able to match the performance anticipated by Ofcom modelling in the early years of LTE rollout?"

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Summary:
State of the Art and Expected Evolution for Smart Scheduling

- Smart scheduling can be seen to improve the benefits of low frequency spectrum. Ofcom has modelled this technique and wishes to understand how well their assumptions align with the state of the art and planned evolution of commercially available products
- A literature survey looks at both standardised and vendor specific aspects and claimed benefits. Vendor interviews at Mobile World Congress and individually provided inputs on timing of commercial availability

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Availability and benefits of commercial scheduling

- Smart Scheduling (SS) is possible in a basic form in release 8 of LTE, although additional support is added to LTE-A (Release 10) to enhance performance:
  - Rel 8 supports frequency selective scheduling which helps mitigate interference.
    Little benefit found from semi static ICIC schemes in loaded networks.
  - Rel 10 supports dynamic ICIC and CoMP which provide benefits to cell edge user throughputs
- Release 10 UEs will be available from late 2013, but it may be 2016 or later before they are dominant in the device mix

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Comparison with Ofcom Modelling Assumptions

- Ofcom assumes an ‘intelligent’ scheduling benefit at low loads only, which aligns well with the low gains found in commercial release 8 LTE with ICIC
- Ofcom assumed gains for frequency domain scheduling are also well aligned with commercial figures
- Ofcom’s overall smart scheduling assumptions are appropriate for release 8 LTE and are applicable for the first few years of rollout up to around 2016. These assumptions may result in an underestimate of user throughput for release 10 infrastructure and UEs which are likely to dominate after this time.

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1 Introduction

Smart Scheduling

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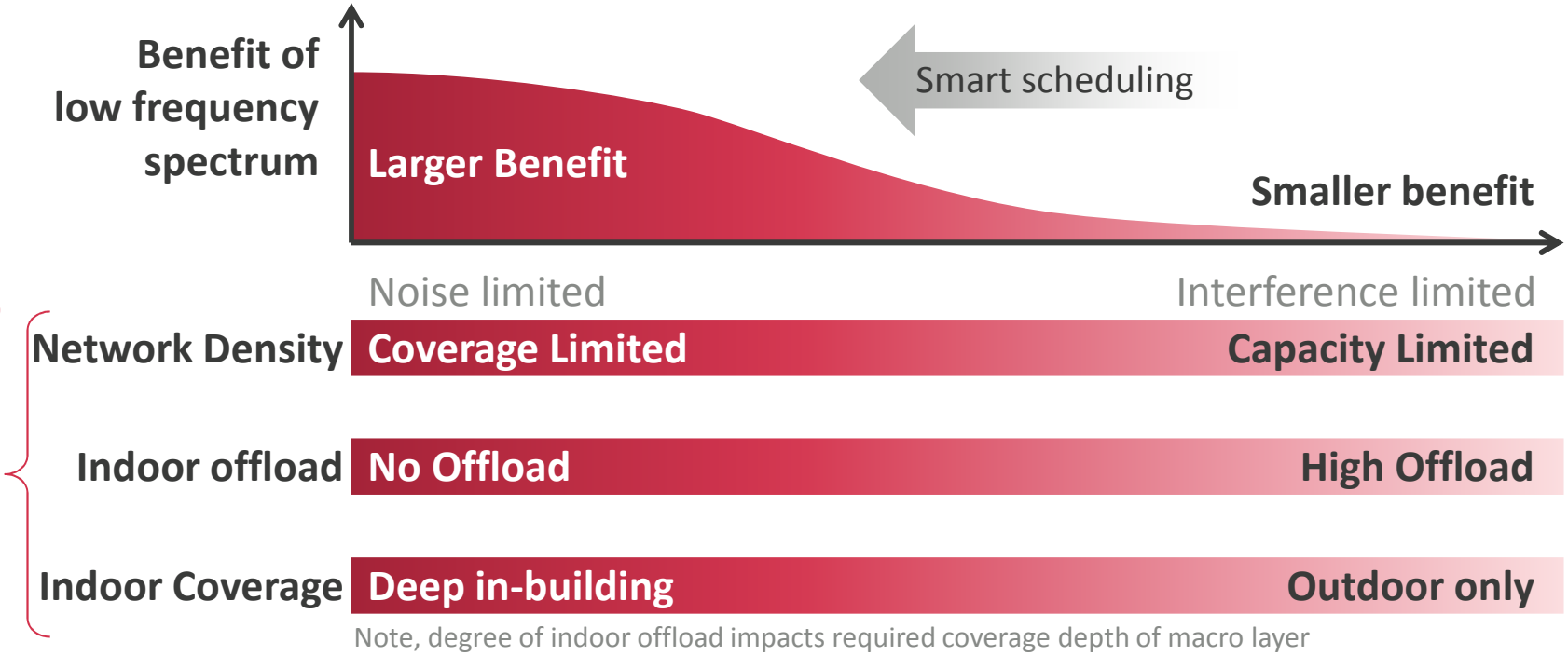
Why are smart scheduling assumptions important?



Other modelling assumptions that impact the benefit of low frequency spectrum and the potential level of additional benefit from smart scheduling

Smart scheduling helps reduce interference, and thus pushes a network towards being noise limited, where benefits of low frequencies are greater

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Ofcom Modelling Assumptions for Smart Scheduling
from Annex 14 of January 2012 Consultation document

- Smart Scheduling [A14.71]
  - Frequency Domain Packet Scheduling with user throughput gains of up to 40%
  - 'Intelligent' scheduling assumption divides the channel into 3 sub-bands and at light loads (<33%) performs N=3 reuse across the network. Once load exceeds 33% the scheme reverts back towards N=1
- Purpose of study is to compare these assumptions with what is currently available or on the roadmap for commercial products

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Literature Survey

2.1 3GPP Specifications

What do the standards have to say about Smart Scheduling?

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"The details of the scheduling algorithm are left to the eNodeB implementation, but the signalling to support scheduling is standardised"

"LTE the UMTS Long Term Evolution",
S. Sesia, I Toufik, M. Baker, Wiley 2009

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3GPP TS 36.300

- TS 36.300 provides an overview of the LTE Radio Access Network (RAN) and key functions
- Section 16 details Radio Resource Management (RRM), which covers scheduling aspects
- These are not specified in detail, rather general guidelines are given
- The standardised 'hooks and eyes' of RRM are specified in 36.133 "Measurements in support of RRM"
- The next few pages show relevant extracts from 36.300, release 10

- "E-UTRAN Overall Description", 3GPP TS 36.300, ver. 10.6.0, Dec 2011, http://www.3gpp.org/ftp/Specs/html-info/36300.htm

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36.300: Dynamic Resource Allocation

- Scheduling is referred to as 'Dynamic Resource Allocation' (DRA) by 3GPP.
- Guidelines are given in 36.300 on what DRA and Packet Scheduling (PS) should achieve, and what standardised measurements should be taken into account:
  - DRA-PS's task is to allocate and de-allocate resources to user and control plane packets
  - Resources include spectral resource blocks, but also buffers and processing resources
  - Sub tasks of DRA:
    - Selection of radio bearers with packets to be scheduled
    - Management of resources including power levels
  - Packet scheduling further must consider QoS requirements associated with different data and signalling flows, channel quality information, buffer status, interference etc.
  - DRA can also communicate with other schedulers to co-ordinate interference

"*E-UTRAN Overall Description*", 3GPP TS 36.300, ver. 10.6.0, Dec 2011, http://www.3gpp.org/ftp/Specs/html-info/36300.htm

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36.300: Inter Cell Interference Co-ordination

- ICIC has the task to manage radio resources to keep control of inter cell interference i.e. a form of multi cell RRM
- Works in both frequency domain and time domain, on uplink and downlink
- Takes into account loading situation across multiple cells
- Frequency domain ICIC techniques include fractional frequency reuse and involve reserving particular resource blocks to certain cells
- Time domain ICIC is based on based on assignment of 'Almost Blank Subframes' in 'aggressor cells'
  - They are 'almost' blank as they contain reference symbols needed to support legacy UEs

"*E-UTRAN Overall Description*", 3GPP TS 36.300, ver. 10.6.0, Dec 2011, http://www.3gpp.org/ftp/Specs/html-info/36300.htm

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Literature Survey
2.2 Books and Articles

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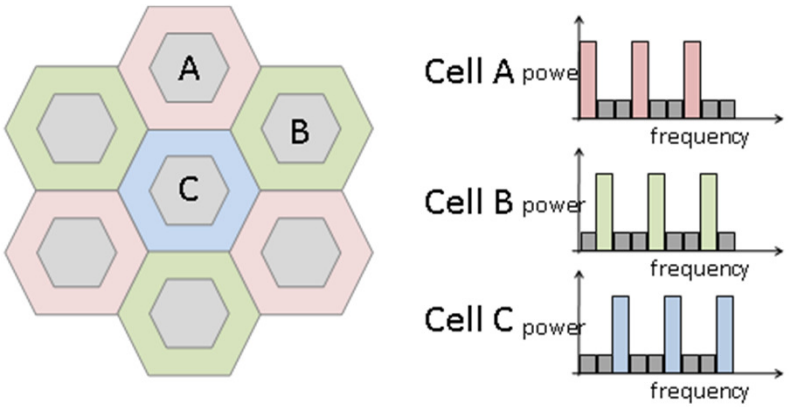
Inter Cell Interference Co-ordination [Sesia]

- The '4G Capacity Gains' study [4G] found that ICIC smart scheduling performed is in effect a form of 'doughnut-ing', which in theory improves overall network throughput

a) UEs in cell centres

b) UEs at cell edge

Capacity in (b) maximised by switching one base station off



Partial Frequency Reuse technique described in [Sesia] illustrates that eNodeBs can schedule according to doughnut principles (albeit for RB subsets within a carrier, as opposed to whole carriers)

[Sesia] "LTE the UMTS Long Term Evolution", S. Sesia, I Toufik, M. Baker, Wiley 2009

[4G] "*4G Capacity Gains*", Real Wireless, January 2011, http://stakeholders.ofcom.org.uk/market-data-research/technology-research/2011/4G-Capacity-Gains/

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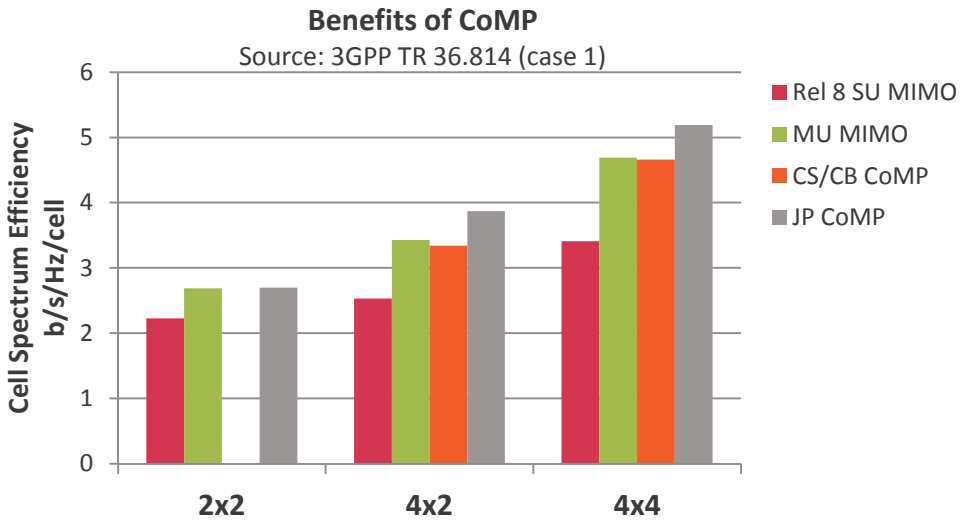
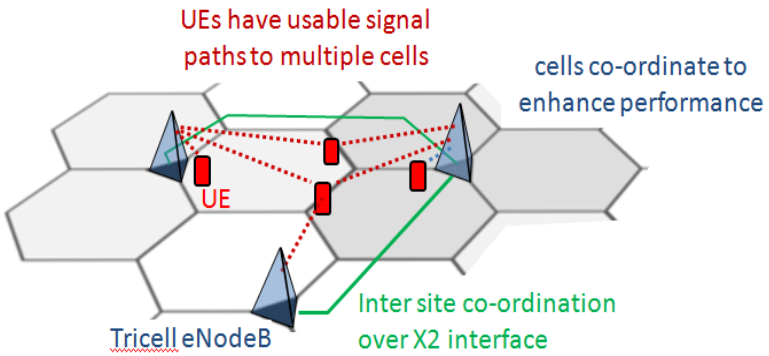
CoMP – A Multi Cell Scheduling Technique





- Co-ordinated Multipoint transmission and reception technology works by exploiting usable signal paths to multiple cell sites.
- Co-ordination of transmission by the network to such UEs can enhance downlink cell spectral efficiency, provided suitable backhaul is available to support the X2 interface between cell sites
  - CoMP gains are sensitive to backhaul latency
  - CoMP is best where spectrum is highly utilised and sites have fibre backhaul – dense urban environments.
- Semi static ICIC available in rel 8 LTE is essentially a basic form of CoMP. Enhanced algorithms are introduced in Rel 10 for Co-ordinated scheduling & Beamforming and Joint Transmission.

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3 Vendor viewpoints

Scheduling is not standardised and is left to vendor implementation. What are they offering?

The vendors' stands at Mobile World Congress 2012 provided an opportunity find out about the features and when they'll be commercially available…

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Example Questions to vendors:

- LTE Infrastructure Vendors were approached at MWC 12 and asked the following:
  - In support of the forthcoming auction, Ofcom would like a better understanding of the performance benefits achieved from commercially available LTE scheduling technologies
  - Regarding Scheduling techniques (e.g. ICIC, eICIC, CoMP, beamforming etc.)
    - What is the status of your development ?(demo, trials, current product etc.)
    - What are the performance benefits?
    - It is of particular interest how such benefits are articulated, whether they given in terms of increases to cell Tput (throughput), User tput, or other metrics.

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Scheduling Techniques Interview

- The following points were made during a telephone interview with a R&D representative from an LTE infrastructure vendor during Feb 2012:
  - Scheduling is not standardised and tends to be specific to individual customer requirements.
  - ICIC and ABSs have been simulated and contributions made to 3GPP. ICIC is on the roadmap but it is not believed to be implemented in a current product.
  - FFR (Fractional Frequency Reuse) has been simulated, but gains were not significant
  - ICIC benefits vary with scenario - need to check <the company's> RAN1 contributions for further details. TR 36.814 provides simulation scenarios including 'het net' environment where ICIC was evaluated.

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Qualcomm Video: LTE Advanced: Range Expansion + Partitioning

- Qualcomm demonstrates in [1] two techniques to improve the performance of LTE-Advanced heterogeneous networks:
  - Range Expansion – effectively an interference cancellation receiver in the UE allowing it to detect reference symbols at very low SINRs down to -18dB
  - Resource Partitioning – dynamically apportions resources in the frequency and time domains between small cells and macrocells in a heterogeneous network (Het net). A multi cell smart scheduling technique
- Source: [1] "*LTE Advanced: Heterogeneous Networks*", Qualcomm, Jan 2011, http://youtu.be/sy_IlmkVhGU

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Qualcomm at MWC 1

- Qualcomm provide UE chipsets for LTE, but also license base station technologies to vendors
- LTE interference reduction wise, they demonstrated 'range extension plus resource partitioning' principally designed to improve capacity in het nets by shifting more load onto the small cells.
- Their demo was linked to a live trial network in San Diego
- **Range Extension: interference cancellation of 'pilots' in UE extends catchment area of small cells in het net**
  - UE Interference Cancellation of the macro's 'Pilots' (RS, sync and broadcast) extends the range that UEs will camp on the small cell at in the presence of a stronger signal from the (higher power) macro.
  - Specified as a UE receiver type in release 10 LTE, QC claims it extends the SINR 'cutoff' down to -18dB (Ofcom current assumption is -5dB)
  - Works with predictable 'pilots' but not data (PDSCH), hence the need for resource partitioning

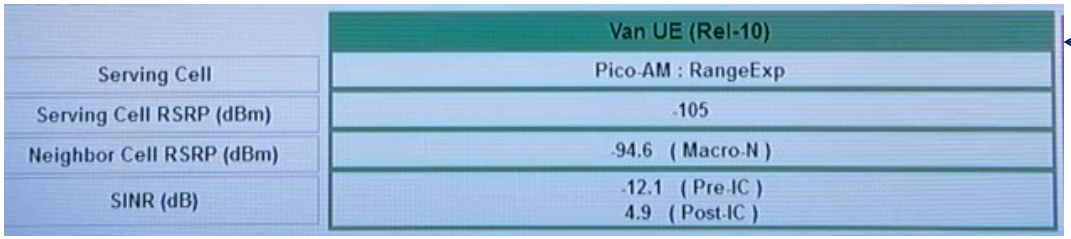

Photo of demo screen taken at MWC 2012 with permission of Qualcomm

← Interference cancellation giving 7.2dB SINR boost allows detection of neighbour cell down to -18dB SINR

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Qualcomm at MWC 2

- **Resource Partitioning: Co-ordination of PDSCH across multiple cells**
  - Time domain partitioning of the PDSCH across multiple cells. Both fixed and adaptive methods were shown – where adaptive allocated RBs depending on the data rate requirements of the UEs.
  - A macro and set of small cells are all time synchronised using GPS (or similar).
  - PDCCH is co-ordinated across the various cells
  - Standardised in rel 10, with RB and ABS usage patterns per eNodeB organised around 40 x 1ms sub-frames
- Benefits:
  - claim 2x network Tput LTE over release 8 for a heterogeneous network of small and macro cells
- Commercial availability:
  - Requires rel 10 UEs with interference cancellation
  - Live trials today, currently IODT (Interoperability Development Testing) between vendors

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Qualcomm – Claimed Performance gains from range extension + resource partitioning

- Median Downlink Data Rate:
  - Rel 8 Macro only 1x
  - Rel 8 Macro + Picos 1.4x
  - Rel 10 Macro + Picos 2.8x
- Per cent UEs with at least 1Mbps
  - Rel 8 Macro only 22%
  - Rel 8 Macro + Picos 38%
  - Rel 10 Macro + Picos 78%
- Source: "*LTE Advanced—The Global 4G Solution*", Qualcomm 2012, http://goo.gl/dNbq5
- **Compared to rel 8, Release 10 Smart scheduling techniques double the median downlink rates and %Users achieving 1Mbps in a het-net scenario**

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NSN at MWC 1

- Demonstrated two types of LTE UL interference reduction
- **1) UL interference awareness and avoidance (Low to medium loads)**
  - Appears to use measurements of interference on different parts of the band to work out the best part of the band to schedule UL transmissions
  - No co-ordination between sites, works on measurements
  - Expect 40% increase in cell edge Tput at low-med loads
  - Commercially available today, and based on LTE rel 8
- **2) UL Interference Rejection: (High loads)**
  - Uplink beamforming to steer nulls in direction of other cell UEs causing UL interference
  - Requires at least 2 Rx antennas at cell site, but better gains with 4 Rx antennas
  - Enhances cell edge performance , but no figure available for how much.
  - Live Air demo today
  - ALU showed a similar approach for DL, but this needs new UE measurements which are still being standardised (rel 11)

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NSN at MWC 2 - DL CoMP with reduced fronthaul bandwidth

- NSN compared DL CoMP at layer 1 with that at layer 2
- CoMP with 'remote radio heads' with 'fronthaul' with layer 1 or layer 2
  - 'Fronthaul' is new term describing the high capacity connection needed between a baseband and a remote radio head – as opposed to backhaul which connects in the other direction from the base station to the core.
- Performance Comparisons:
  - No CoMP = baseline Estimate L1 fronthaul is 12x UE Tput
  - L1 CoMP 2x Cell edge UE Tput for fronthaul of 24xUE Tput
    - L1 CIPRI or ORI typically needs several GBPs of Fronthaul
  - L2 CoMP 1.2x over no No Comp, for 1.2x UE Tput
  - Front haul running over GigE speeds
- Commercial availability 2013

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Samsung 'Smart LTE' C-RAN

- Samsung demonstrated Interference co-ordination through C-RAN where C stands for Cloud or Centralised
- Works today on rel 8 or 9 with no X2 needed
- No further information provided of how interference is managed
- Claimed benefits are 2x Cell Edge UE Tput
- Future plans to implement CoMP etc., but could not be specific about dates

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Alcatel Lucent – Downlink Beamforming Demo

- Demonstrated downlink beamforming to reduce interference
- Showed C/I benefit of the different schemes:
  - Baseline (No beamforming) 0dB C/I gain (No angular separation between UEs)
  - Fixed Beam : 0-5dB C/I gain
  - “Conjugate beamformer”, 5-10dB C/I gain
  - “Zero forcing”:, 20+ dB C/I gain
- Scheduler can select pairs of UEs with angular separation.
- Benefits: ~30% cell Tput (zero forcing)
- Requires new CSI from UEs which is still being standardised (in rel 11)
- Availability is therefore several years out, and will not work for legacy pre rel 11 UEs, so full benefits not available until majority of UEs are rel 11 or later

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Alcatel Lucent – Small Cell Interference Management

- Small cell interference management:
  - Live Telefónica trial around MWC demonstrating ALU's metrocell.
  - We understand that this trial makes use of rel 8 interference awareness features to avoid problems
  - Techniques include Frequency Selective Scheduling (FSS), power control, etc.
- FSS available today
- FSS claimed to have 25% benefit to cell tput compared to non FSS case.

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Smart Scheduling benefits and timing

Vendor	Technique	Claimed Benefits	Required LTE Release	Status Feb 2012	Commercial Availability
Qualcomm	Range expansion	Boosts SINR of 'pilots' (by 7dB in demo). Enables cell detection to -18dB SINR	Rel 10 type UEs network sync	Live air Demo	Rel 10?
Qualcomm	Resource Partitioning	2x network Tput. Doubles %UEs with>1Mbps from 38% to 78%	Rel 10 eNB & UE	Live air Demo	Rel 10
NSN	UL Interference avoidance (low loads)	40% increase in cell edge UE Tput at low loads (no X2 needed)	Rel 8	in product	Now
NSN	UL interference cancellation (high loads)	Beamforming/ null steering. Enhanced cell edge performance (not quantified)	Stated Rel 8, but similar ALU technique requires rel 11	Live air Demo	Rel 11?
NSN	CoMP at L1 and L2	L1 CoMP 2x cell edge Tput L2 CoMP 1.2x cell edge Tput (significant reduction in fronthaul bandwidth)	Rel 10 eNB and UE	Simulation	2013 stated
Samsung	Smart LTE C-RAN	Interference co-ordination with Centralised RAN. 2x cell edge Tput	Rel 8, no X2 (but high capacity fronthaul)	Commercial in LTE	Now
ALU	DL Beamforming	Up to 20dB C/I gain with most advanced beamforming technique. Claim 1.3x cell Tput	Rel 11 UE's CSI reports	live air demo	requires high penetration of Rel 11 UEs
ALU	Small cell Interference management (Freq Sel Sched)	1.25x network Tput (no X2 needed)	Rel 8	Live air demo	Now

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Summary of benefits per release

- Release 8:
  - 1.4x cell edge Tput and 1.2x network capacity with Frequency Selective Scheduling at light loads (no X2 co-ordination needed)
  - 2x cell edge Tput with centralised RAN (needs high capacity fronthaul)
- Release 10/11:
  - 2x cell edge Tput with CoMP over X2 (needs high capacity low latency backhaul)
  - 2x capacity in het net (Rel 10 UEs required & time synchronised network)
  - 1.3x capacity with DL beamforming (Rel 11 UEs required)

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4 Timing and Commercial Availability

A consideration of the benefits available from the smart scheduling based on standardisation, commercial availability and enablers to deploy based on loading expectations in UK networks

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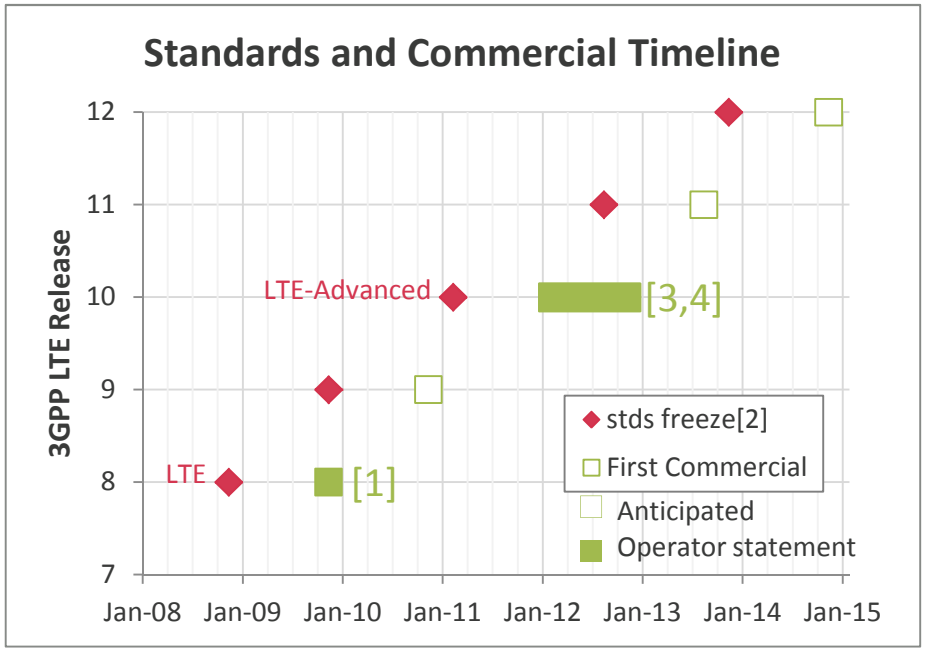
Standards and Commercialisation



- A given release of the Standards continuously evolves and can be corrected years after products are commercially available
- Functional 'Freeze' dates shown here mean that no new features can be added, although details may still need to be agreed
- First commercial deployment for release 8 was one year after the standard freeze date
- First commercial Rel 10 base stations were announced in Feb 2012 (also 1 year after the rel 10 freeze) and will become available for deployment during the rest of the year [3,4]

[1] "*TeliaSonera launches world's first commercial LTE network*", 14 Dec 2009, http://goo.gl/oMh3o
[2] "*3GPP release dates*", http://www.3gpp.org/releases. (Stage 3 dates assumed)
[3] "*ZTE Debuts LTE-A Inter-Band Dual-Carrier Commercial Base Station at MWC*", 2012-02-27, http://goo.gl/gpaMX
[4] "*LTE-A: Trailblazing Towards 4G*", ZTE, http://goo.gl/hqFfV
[5] "*TeliaSonera reaches 100,000 LTE users; prepares for upsurge this year*", http://goo.gl/952Ob

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LTE-A Infrastructure available from 2012

- LTE-Advanced (with eICIC and CoMP for scheduling and CA for CoMP)
  - "ZTE is now working hard to develop LTE-A technology and has made good inroads to this end. The company plans to roll out commercial LTE-A products in 2012. This will allow people to enjoy feature-rich services and high-speed connectivity using mobile broadband.", '*LTE-A: Trailblazing Towards 4G*', ZTE, http://goo.gl/hqFfV
  - "It is expected that LTE-Advanced will first be commercially available in 2012, with wider deployments by 2015." 'LTE Advanced', 4G Americas, http://goo.gl/0YSdB
  - "AT&T to deploy LTE-Advanced in 2013", Fierce Wireless, Nov 2011, http://goo.gl/FztYP
  - "Sprint will deploy LTE-Advanced in the first half of 2013", Fierce Wireless, Oct 2011, http://goo.gl/3XvJk
  - "Ericsson expects commercial LTE-Advanced services by 2013", Total Telecom, June 2011, http://goo.gl/wjzrB
  - "To further increase download speeds and provide customers with a high-quality mobile broadband service experience, Vodafone Germany plans to introduce LTE 800MHz and LTE 2600MHz into its existing network within three to five years", '*Vodafone Germany: Golden frequency band transforms countryside*', Huawei Magazine, Sept 2011, http://goo.gl/bTGE8
- Commercial LTE-Advanced Equipment available from 2012
- First Deployments in 2013
- Wide scale deployment and device penetration by around 2015
- In Germany: second 2600MHz band in addition to initial 800MHz band during 2014-2016

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Comments from TMO US about rel 10 availability

- ***"FierceWireless:* You are going to deploy LTE Release 10, which is LTE Advanced. Do you plan to differentiate with LTE Advanced?**
- **Ray**: No one has a Release 10 network today. Our intent is to deploy Release 10-capable equipment. The hardware we put in the field will be software capable for Release 10. There will be a lot of flavors of ... LTE-Advanced. Carrier aggregation is in LTE Advanced and that's a big deal. That may or may not make a big different to the customer experience. There are a whole host of advantages to LTE Advanced. Carriers may say they will do LTE Advanced but there's a lot to it--devices, backhaul, etc.
- For us, obviously, we are only now moving to finalizing our LTE equipment and we are pushing hard to get it Release 10-capable. When we talk to the chipset guys, they say there will be availability in the latter half of 2013, but it will be in higher-end devices. I think you will see more in 2014. "
- Source: '*T-Mobile's Ray on the upside of LTE Advanced*', FierceWireless 14th March 2012, bit.ly/GzAbwj

- **Summary: First high end LTE-A (r10) devices in 2H 2013, more in 2014.**

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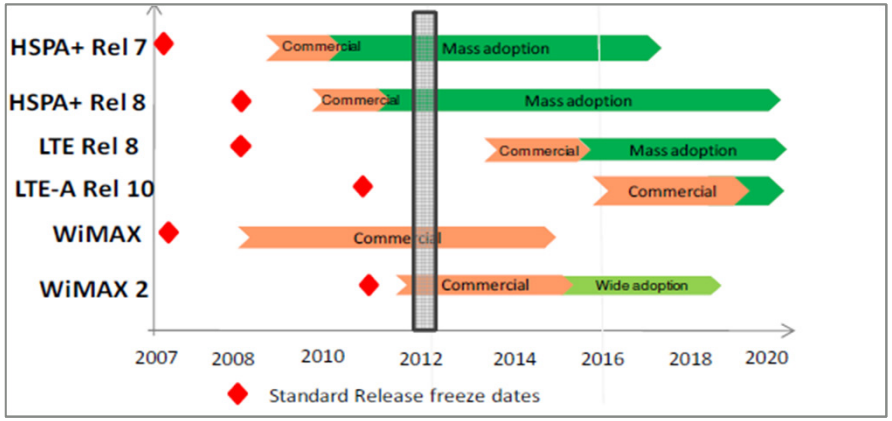
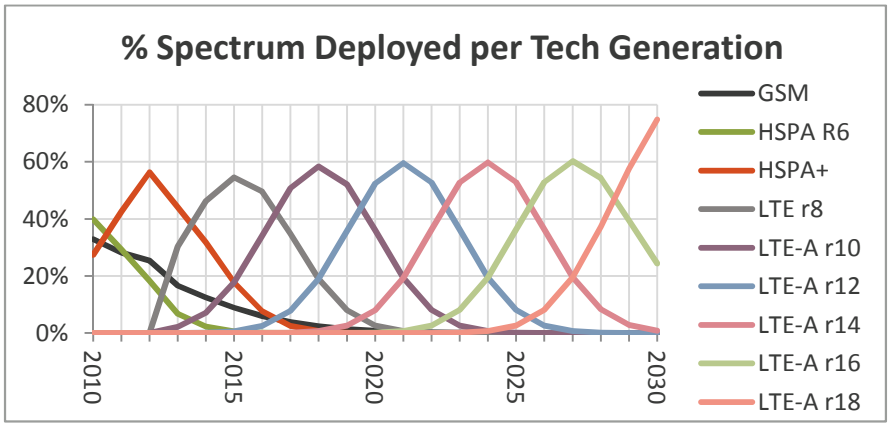
Rel 10 devices in the mix lag behind infrastructure

- Although rel.10 infrastructure may be rolled out from 2013, rel.10 devices are also needed to enable the features
- In general the device generation mix lags behind that of the infrastructure.
- Assumptions in [1,2] show release 10 being significant in the mix beyond 2015, representing a lag of 2-3 years.

- Sources
  - [1] "*4G Capacity Gains*", Real Wireless on behalf of Ofcom, Jan 2011, http://goo.gl/QbW22
  - [2] "*Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030*", Real Wireless on behalf of Ofcom, Mar 2012



[1]



[2]

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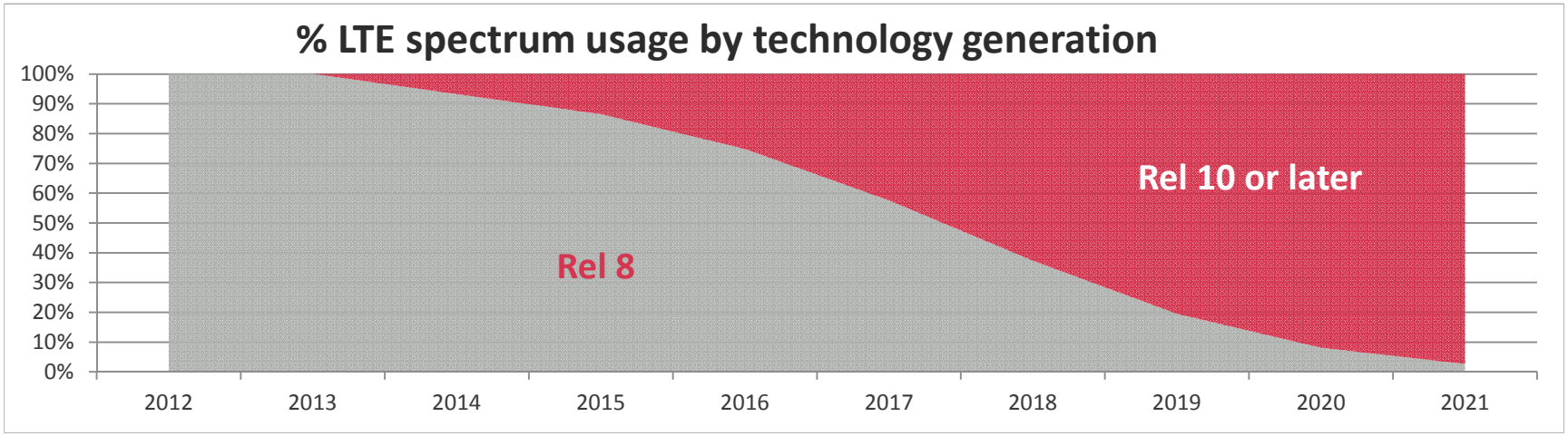
Spectrum Usage (incorporating Device Mix)



- This graph is based on an interpretation of the '*% Spectrum Deployed per Tech Generation*' graph, which considers the usage of spectrum by 3GPP generations from 2012 to 2030
  "*Techniques for increasing the capacity of wireless broadband networks: UK, 2012-2030*", Real Wireless on behalf of Ofcom, Mar 2012, http://www.realwireless.biz/realwireless/wp-content/uploads/2011/11/Final-report-Capacity-Techniques-for-Wireless-Broadband-v1_15.zip
- A more accurate view of device availability will be obtained from the final report of another Real Wireless study to '*Recheck status of LTE and HSPA devices, especially as regards 900 MHz support*" which was in progress during this work

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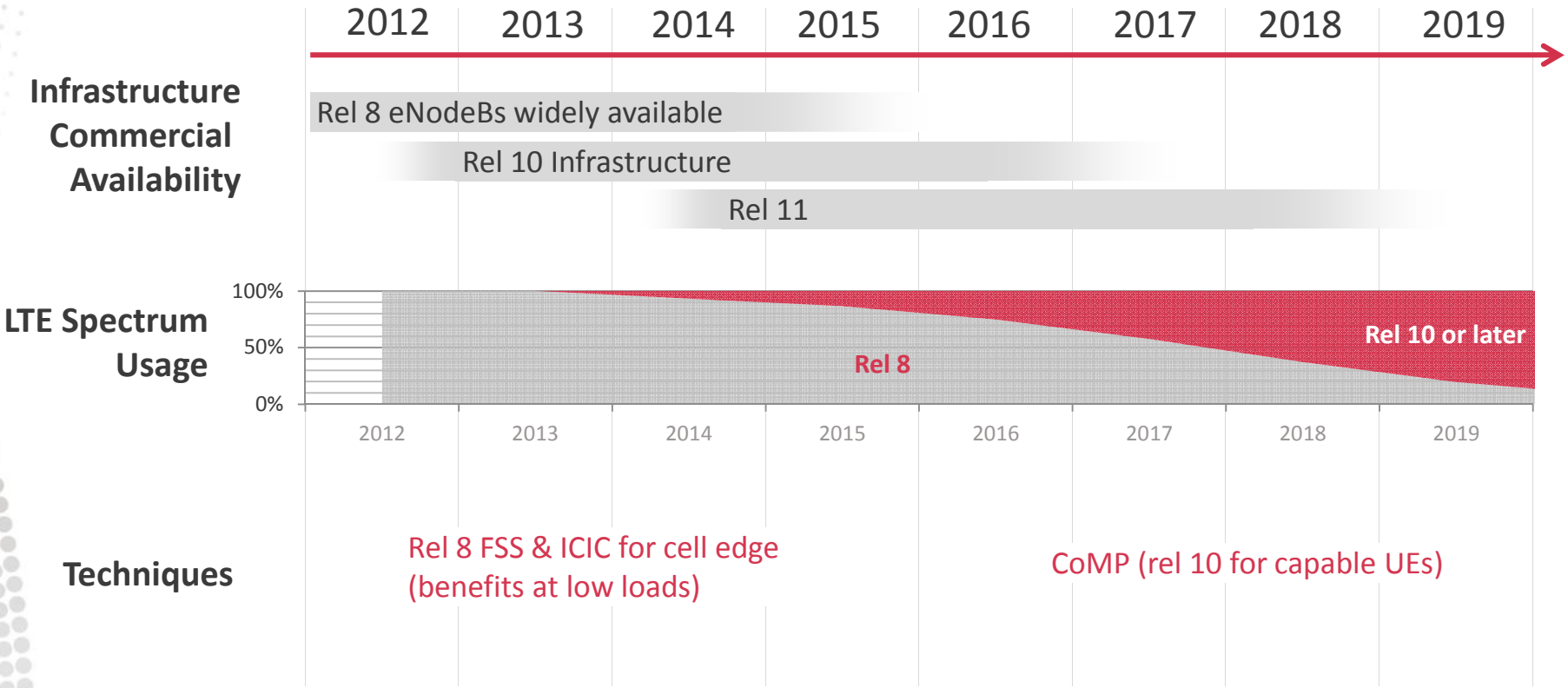
Timeline of enablers towards Smart Scheduling



Since UE support is needed, Release 8 based features likely to be dominant until around 2016

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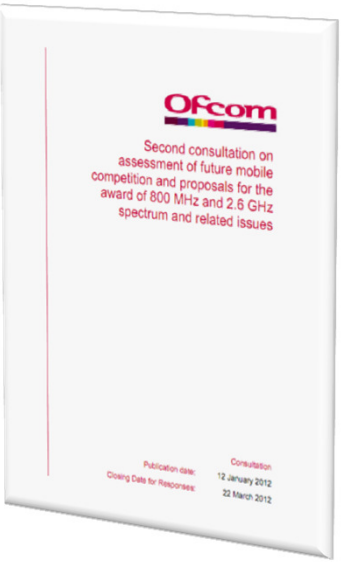

5 Comparison with Ofcom Modelling

How does the latest review of commercial performance and timing compare with the 2011 assumptions used for modelling?

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Annex 14.69: Other Cell Interference

A14.69 Network or system loading is accounted for, when calculating other cell interference, by multiplying the interference power from each sector by an interference probability. In response to concerns over our March 2011 assumptions on loading, the interference probability is now calculated in accordance with two different algorithms covering the two extremes in terms of impact of interference:

1) random allocation in which it is assumed that the resource blocks in each cell are allocated on a purely random basis (used for our 'Min var' case); and
2) intelligent allocation where each of the resource blocks in each cell are allocated on a basis that accounts for the scheduling of the corresponding resource blocks on other sectors of the serving cell in order to minimise inter cell interference (used for our 'Max var' case).

- Random being the baseline case with no 'smart' scheduling. Other cell interference is proportional to network loading [A14.72]
- Assume that this is the same baseline used by vendors when stating the benefit of their smart scheduling schemes

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14.79 Intelligent Scheduling Algorithm

'intelligent' removes first tier Interference at low loads

Figure 5: Illustration of sector arrangement in intelligent loading

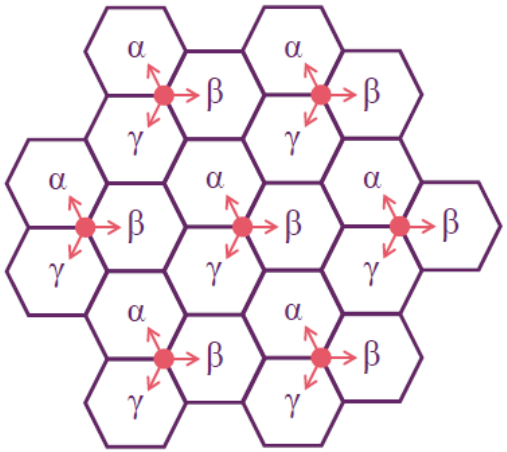
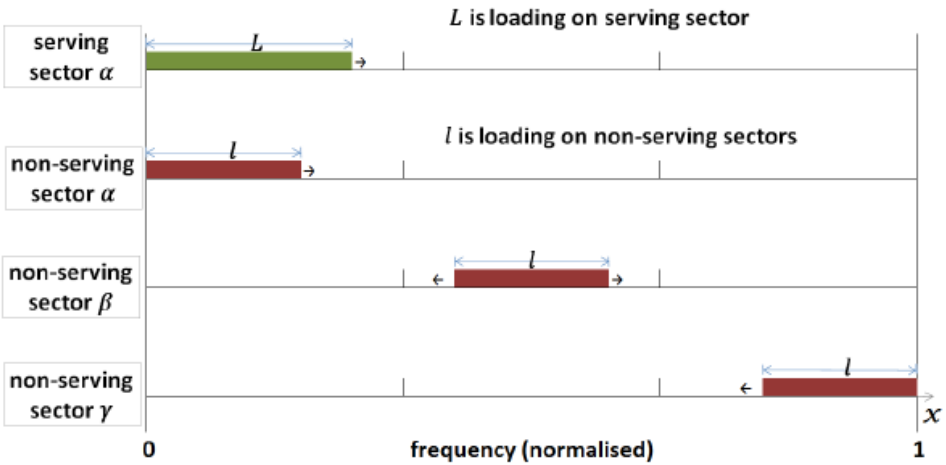


Figure 6: Intelligent scheduling of sectors



- The 'intelligent' scheme represents static fractional frequency reuse with N=3, where the channel is divided into 3 sub bands, and adjacent cells in the network are planned to avoid using the same sub band for loads less than 33%
- The text states this co-ordination is only around the same site, however co-ordination between sites is also important to reduce interference from inter-site cell edges as well as adjacent sector cell edge
- In practice in an irregular network, this would require either fixed, frequency planning or more likely some degree of network co-ordination over the X2 interface between base stations

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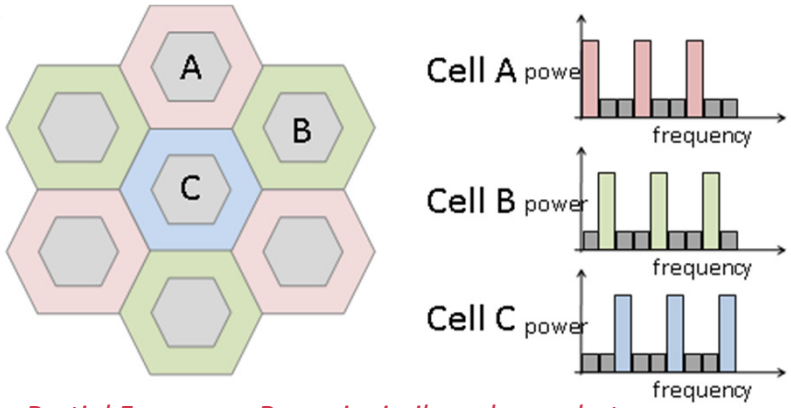
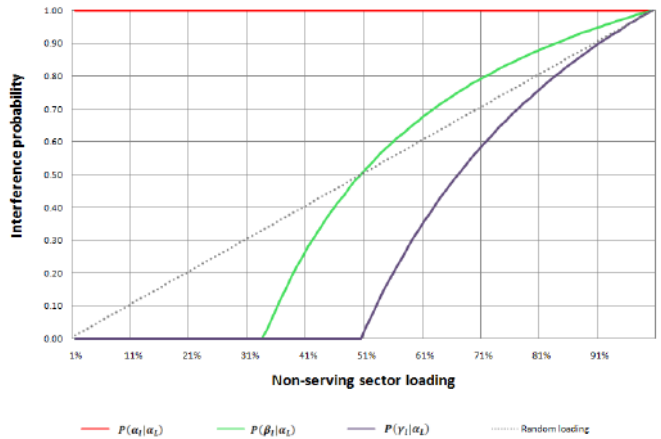
14.79 Intelligent Scheduling Algorithm



Partial Frequency Reuse is similar scheme, but co-ordinates only on UEs near to the cell edge

Figure 7: Interference probability vs non-serving sector loading – serving sector loading equals non-serving sector loading



- The intelligent scheme is similar to the scheme described in [Sesia] (see §2.2),
- As described in 14.79, co-ordination is applied across the whole cell rather than just the outer cell edge
- The intelligent scheme out performs random at loads less than around 50%. Beyond this the random and intelligent schemes have similar performance.
- Saving the frequency co-ordination only for users who most need it may result in better performance for more highly loaded networks (>50%).
- For low loads (<50%) the intelligent scheme is a good model for removing interference from the first tier of adjacent cells (there will still be interference from the next tier where the sub band is reused)

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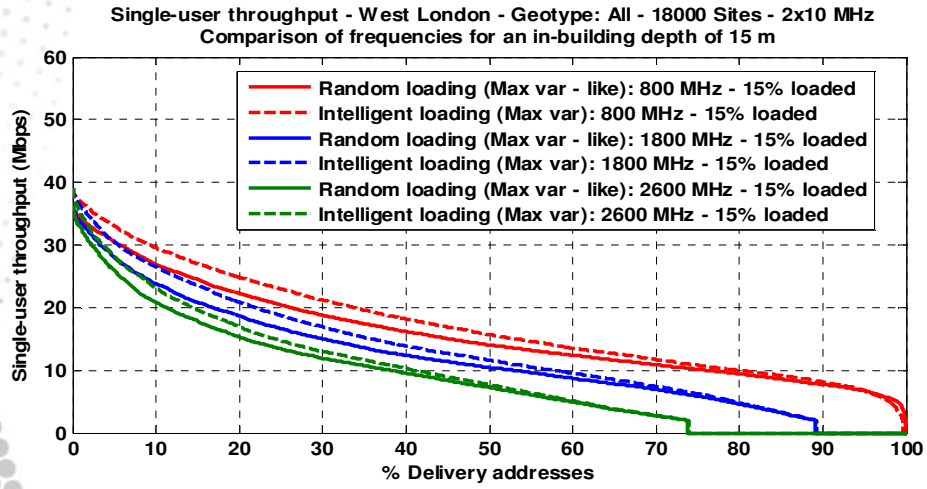
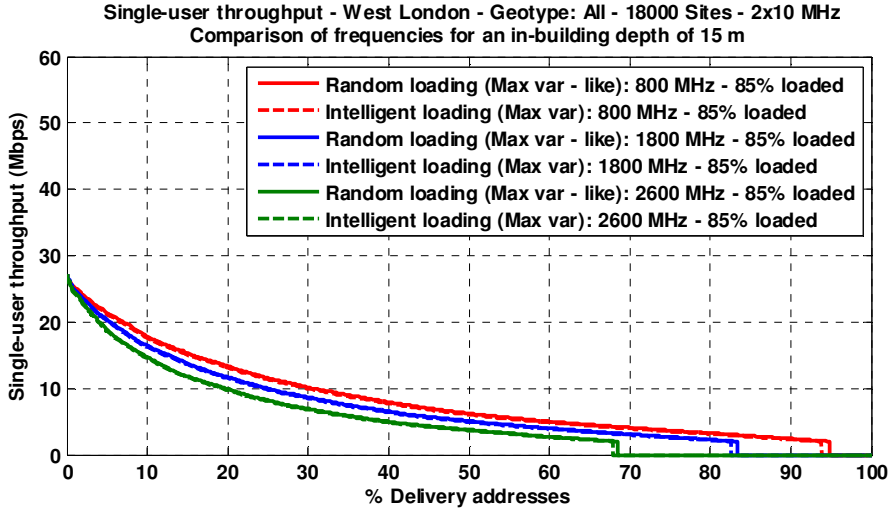
Comparison of smart scheduling benefits





- Ofcom modelling shows intelligent scheduling improves single user throughput at low networks loads (15%) but not at higher loads (85%). Benefits are not seen for worst case (cell edge) UEs as they are likely to be noise limited and therefore not benefit from interference reduction.
- This aligns with comments from NSN and NEC that the semi static or fixed frequency reuse schemes were of little benefit in loaded networks.
- NSN commented that (dynamic) frequency selective scheduling was the best approach for release 8. Benefits of this are modelled as frequency domain packet scheduling (next slide).

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Frequency Domain Packet Scheduling Gain

Frequency domain packet scheduling

A14.112 Frequency domain packet scheduling (FDPS) exploits the fact that an LTE carrier is split into multiple sub-carriers and that these sub-carriers are grouped together in frequency and split by time to form individual physical resource blocks (a 5 MHz carrier has 25 resource blocks whilst a 20 MHz carrier has 100). At any instant in time different users can be allocated a different number of physical resource blocks depending on their instantaneous demand and their signal quality. If the channel quality is significantly different for different physical resource blocks (which is typically the case for macro cellular networks with bandwidths equal or greater than about 5 MHz) then LTE can exploit this by optimally scheduling users on physical resource blocks with the best channel quality at their location. This can lead to a FDPS gain which for pedestrian users can be of the order of 40% for a 10 MHz system bandwidth. To achieve this level of gain however there needs to be multiple users all demanding a service that requires a relatively small proportion of the resources available in the cell at any instant of time. If there are just a few users requiring a large proportion of resources then the gain is reduced.

A14.114 A FSPS gain is applied to the calculated single-user throughput results to account for improved performance from scheduling users on groups of resource blocks whose SINR is highest for that user.

A14.115 The calculation is in three steps as follows:

a) Calculate a factor between 1 and 1.4 using the following equation[44]:

$$\gamma = 1.4 - 0.729 \times e^{-0.599U} \quad (18)$$

Where U is the number of simultaneous users (for a given guaranteed data-rate service) who could be supported at a particular location if the single-user throughput was shared equally between them.

b) Multiply the factor (γ) calculated in step a) by an additional bandwidth dependent factor (δ)[45]. The value of (δ) for each carrier bandwidth is given in Table 13 below:

Table 13: FDPS gain bandwidth factors

Bandwidth	5 MHz	10 MHz	15 MHz	20 MHz
(δ)	0.9643	1.000	1.0179	1.357

c) The single-user throughput per resource block (in the absence of FDPS) is multiplied by the product of γ and δ.

- Ofcom modelling assumes FDPS gains of up to 40% to user throughputs (dependent on the carrier bandwidth and number of users)
- This ties in well with NSN claims at MWC12 on the benefits of their Frequency Selective Scheduling demonstration.
- NSN claimed 1.4x increase in cell edge user throughputs with FSS. They associated this with interference avoidance in adjacent cells, although some of this would be available from multi-user diversity too.

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Ofcom assumptions for 'intelligent' scheduling

- The assumed scheme provides benefits at low loads only
- Several vendors stated that they see little benefit from semi static fractional frequency reuse schemes in practice today, and only dynamic interference co-ordination (frequency selective scheduling) provides worthwhile gains for cell edge users at higher loads
- This aligns well with Ofcom scheduling assumptions, which at high loads only the frequency domain packet scheduling gains provide benefit.
- Enhanced co-ordination and CoMP in rel 10 are likely to provide further benefits to cell edge user throughput
- **Ofcom assumptions fit well with rel. 8 LTE, but may underestimate cell edge user throughput for rel 10 LTE. However, it will be 2016 or later before supporting release 10 UEs are significant in the device mix.**

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