LTE Static Simulations
V2020 Q2 (10.0.4)

Algorithms and Outputs relating to the Simulator

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VERSION HISTORY

Version	Date	Author	Comments
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1.1	15/04/2011	V. Kontogeorgos	Updated
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1.6	14/07/2011	A. Lawrow	Version 8.0. Added info on 'User Limit' failures.
1.7	12/10/2011	A. Lawrow	Added info on Terminal Info arrays.
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1.9	09/02/2012	A. Lawrow	Use new definitions of EPRE and PPRE.
2.0	17/02/2012	V. Kontogeorgos	Version 8.0
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2.3	24/04/2012	V. Kontogeorgos	**Version 8.0.1**
2.4	30/04/2012	A. Lawrow	Update RS EPRE calculation
2.5	04/05/2012	A. Lawrow	Updated instantaneous DL RS Power formula
2.6	19/07/2012	A. Lawrow	Corrected CE/CE power scale factors in ICIC formulas
2.7	05/11/2012	A. Lawrow	Updated formula for mean interfering power for RSSI calculation.
2.8	05/12/2012	V. Kontogeorgos	Updated Spatial Diversity
2.9	06/03/2013	A. Lawrow	Version 8.1. New carriers overlap calculations
2.12	10/05/2013	V. Kontogeorgos	Text and figure for carriers overlap calculations Added Multi User Gain Arrays for PF Added Total Max EiRP Added MBR for non-RT Services Bearer Selection Methods Updated Nth DL Loss array description Added UL/DL User Throughput Report Added UL/DL Achievable Throughput arrays Added UL RBs required for Coverage array Added UL RBs Used (Time-Average)
2.13	07/10/2013	V. Kontogeorgos	MIMO calculations - var units updated
3.0	12/02/2014	V. Kontogeorgos	**Version 9.0**
3.1	12/02/2014	V. Kontogeorgos	Added TTI Bundling - Per cell bearer activity factors Added RS and Traffic SINR cell MIMO thresholds
3.2	18/02/2014	V. Kontogeorgos	Added UL Bandwidth Allocation Methods
3.3	12/03/2014	V. Kontogeorgos	Updated Simulator Reports Added Carrier Aggregation arrays Added Multiple-technology arrays
3.4	24/03/2015	V. Kontogeorgos	Added Inter-technology Interference
3.5	10/06/2015	M. Mahendrarajah	Formula (96) updated, RSRP = PPRE/L
4.1	19/11/2015	V. Kontogeorgos	**Version 9.1** Added Inter-eNodeB Carrier Aggregation - Arrays
4.2	05/02/2016	A. Lawrow	Removed MCH completely. Use appropriate frequency overlap in EPRE formulas. Removed old time-overlap completely. Added overview of LTE Interference modelling. New sections on time-overlap and element-overlap factors. New sections giving general forms for UL received power, DL received EPRE, MBSFN calculations, and RSSI
4.3	09/02/2016	A. Lawrow	Express all old SINR denominators as special cases of the general formula for received DL EPRE
4.4	04/03/2016	A. Lawrow	Added MBSFN dependencies to array table
4.5	23/03/2016	V. Kontogeorgos	Added DL/UL ABS Percentage, CRE Delta and

			Nth Best RSRP adjusted by CRE arrays
4.6	05/05/2016	A. Lawrow	Added info on MBSFN coverage probabilities
4.7	31/05/2016	V. Kontogeorgos	Added Terminal Info Percentage Served (Tech Type), Joint Cell Leakage report
4.8	08/07/2016	A. Lawrow	Added UL/DL MIMO Order Arrays
4.9	13/07/2016	A. Lawrow	Corrections to inter-tech interference
5.0	01/12/2016	A. Lawrow	Fixed bad references in ICIC section.
5.1	31/01/2017	V. Kontogeorgos	Updated dependencies for Best Server by RSRP, LOS
5.2	14/11/2017	V. Kontogeorgos	**Version 10.0**
5.3	24/01/2018	A. Lawrow	Added section with beamforming equations.
5.4	26/01/2018	A. Lawrow	Updated AAS section with new transmission modes.
5.5	30/01/2018	A. Lawrow	Added description of beamforming arrays and reports.
5.6	27/11/2018	A. Lawrow	Corrected equations in inter-tech interference section. Corrected description of UL bandwidth allocation methods.

CONTENTS

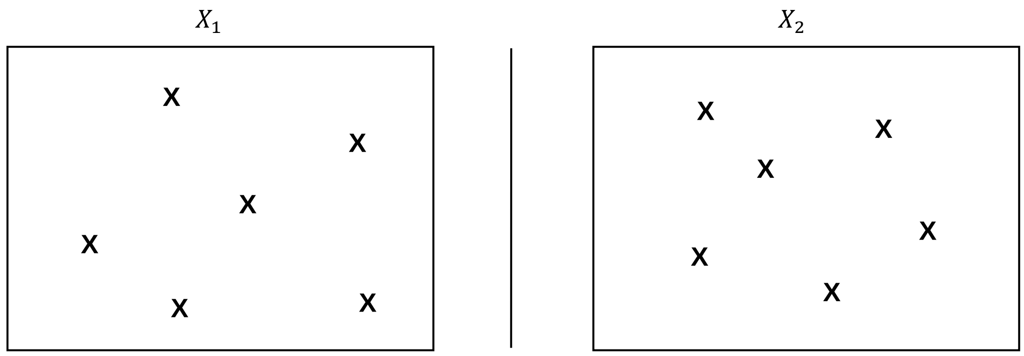
1 WHAT IS A SNAPSHOT?

1.1 RANDOMNESS IN A CELLULAR NETWORK

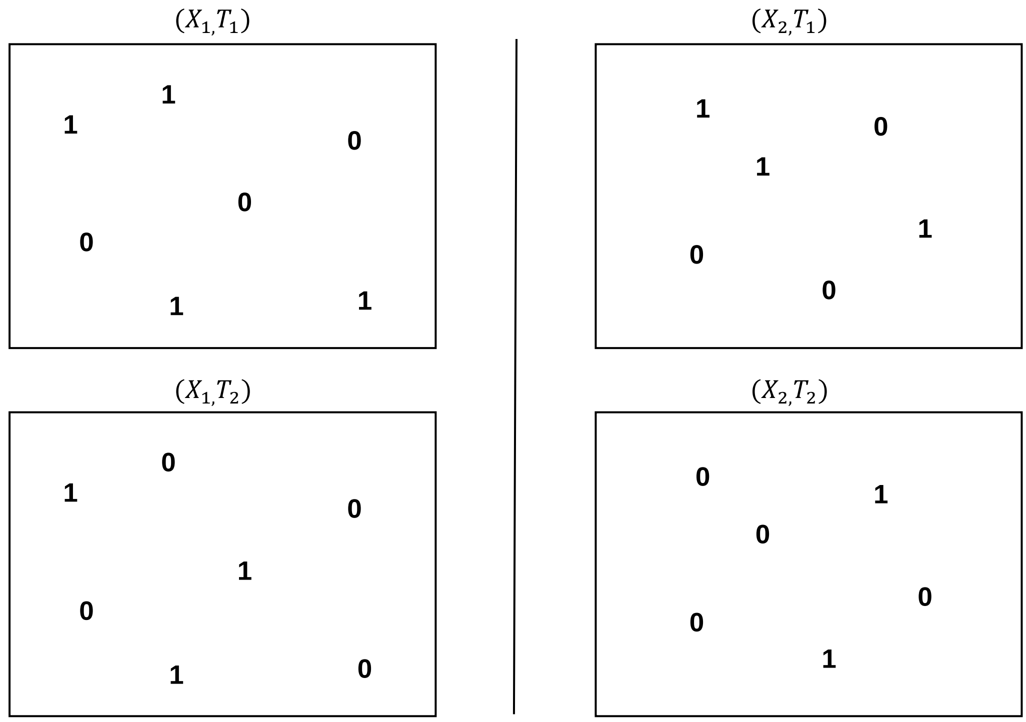
In a simulation of a cellular network there are two main types of randomness that one needs to consider.

- *Spatial randomness in the location of terminals.*
- *Temporal randomness in the activity of terminals.*

We shall consider the spatial domain to be discrete and consisting of a large number of pixels (bins) some of which will contain terminals. Each possible pattern of terminal locations has an associated probability of occurrence. We can label these spatial patterns X_1, X_2, etc and represent the corresponding probabilities of occurrence by $P(X_1), P(X_2)$, etc. An example of two spatial patterns $X_1$and X_2 are shown below.



Each spatial pattern has many possible configurations of transmitting and non-transmitting terminals. Two such configurations for the spatial patterns $X_1$and X_2 are shown below, with 1 representing a transmitting terminal, and 0 a non-transmitting terminal.



We call each of these patterns a *spatio-temporal pattern* to highlight the fact that we have specified spatial locations of terminals and also their temporal state (transmitting/non-transmitting). We can label the spatio-temporal patterns for spatial pattern X_1 as follows $(X_{1,}T_1)$, $(X_{1,}T_2)$ and etc and their probabilites of occurrence $P(X_{1,}T_1)$, $P(X_{1,}T_2)$ and etc. Note that the probability of occurrence of a spatio-temporal pattern $(X_{i,}T_j)$, is proportional to the probability of occurrence of the spatial pattern X_i:

$$P(X_{i,}T_j) = P(X_i)P(T_j|\, X_i). \qquad \textbf{(1)}$$

One can think of a spatio-temporal pattern as being a picture of a real network at a random instant in time. This is what most people have in mind when one mentions a simulation ‘snapshot’, but a snapshot in our Simulator represents something slightly different, as explained below.

The *ideal* static simulation would calculate an average quantity (e.g. the average noise rise on a cell) by performing a *weighted sum* over the set of *all* possible spatio-temporal patterns $(X_{i,}T_j)$, with the weight for a pattern being its probability of occurrence. So the average of some quantity F would be given by

$$\overline{F} = \sum_{X_{i,}T_j} F(X_{i,}T_j)P(X_{i,}T_j). \qquad \textbf{(2)}$$

We can split this into separate spatial and temporal sums:

$$\overline{F} = \sum_{X_i} P(X_{i,}) \sum_{T_j} F(X_{i,}T_j)P(T_j|X_i). \qquad \textbf{(3)}$$

The summations in (2) and (3) are over *every* conceivable pattern of terminal locations and activities, including the unlikely ones, so clearly some simplifications are necessary in any practical static simulator.

Simplification 1: Model *spatial* randomness *explicitly* by sampling.

This simplification is the most common one made in static simulations, and it is used universally. Instead of considering *all* spatial patterns, we consider a set of N sample spatial patterns drawn from the distribution of all spatial patterns. The first weighted sum in (3) can then be approximated by a simple average over the set of N sample spatial patterns:

$$\overline{F} \approx \frac{1}{N} \sum_{X_i} \sum_{T_j} F(X_{i,}T_j)P(T_j|X_i). \qquad \textbf{(4)}$$

Spatial randomness is therefore handled *explicitly* by considering a set of sample spatial patterns that have been selected in a random and unbiased way. There is still the issue of how to handle the different temporal states for each sample spatial pattern. There are two main approaches we can use:

- Model temporal randomness *explicitly* by sampling. (Simplification 2).
- Model temporal randomness *implicitly* with time-averages. (Simplification 3).

Simplification 2: Model *temporal* randomness *explicitly* by sampling.

This simplification is fairly common but has some drawbacks as explained below. Firstly, as in the previous simplification, one selects a sample spatial pattern from the set of all possible spatial patterns, making sure that the selection is made in a random and unbiased way. One then assigns a random ‘activity flag’ (1 or 0) to each terminal in the pattern, to indicate if the terminal is transmitting or not. The probability of assigning a ‘1’ to a terminal is just the service activity factor (% resource element [RE] usage) for that terminal. This ensures that activity flags are assigned in a random and unbiased way. The weighted sum over the set of all spatio-temporal patterns in (2) can be approximated by a simple average over the set of N sample spatio-temporal patterns:

$$\overline{F} \approx \frac{1}{N} \sum_{X_{i,}T_j} F\left(X_{i,} T_j\right). \quad \textbf{(5)}$$

If we called a spatio-temporal pattern a 'snapshot' then the above formula simply says that we can approximate $\overline{F}$ by performing a simple average over the snapshots. This simple average works because the sample spatio-temporal patterns are selected in a random and unbiased way. Also note that this averaging *explicitly* accounts for spatial randomness and *explicitly* accounts for temporal randomness.

There are problems with assigning 'activity flags' to terminals however.

- For low activity services, the user can do 100s of snapshots and never set an activity flag, and therefore certain outputs may not have any results. For example, a simulation report may say that many users are served on a cell but that there is no throughput on the cell. Forcing the user to run 1000s of snapshots is unacceptable in a commercial tool, so we either have to remove the problem outputs or calculate them some other way.

For the above reasons, we do *not* use Simplification 2 and use the following simplification instead.

Simplification 3: Model *temporal* randomness *implicitly* with time-averages.

As before, one selects a sample spatial pattern from the set of all possible spatial patterns, but now we completely remove the activity flags from the randomly scattered terminals. Each terminal is therefore neither instantaneously active nor instantaneously inactive, but rather represents a sort of 'time-averaged' entity. Essentially, this means that when we examine the interference that the terminal produces, or the resources it consumes, we use the time-averages for these quantities, and we calculate these time-averages *implicitly* by using activity factors (*% RE usage*) to scale values.

So in our Simulator, a 'snapshot' does not represent a random instant in time for a random distribution of terminals, but rather '***the average instant in time for a random distribution of terminals***'. The snapshot represents the average instant because all the measures of system load (i.e. UL interference, DL interference, resource usage, and throughput) are time-averages.

It is still valid to perform simple averages of quantities over our snapshots. However, averaging over the snapshots now *explicitly* accounts for spatial randomness only. The temporal randomness is now handled *implicitly* within each snapshot through the use of time-averages in our calculations. Time-averages feature in the evaluation of both coverage and capacity as described below.

1.2 AVERAGING IN COVERAGE AND CAPACITY EVALUATIONS

All our link budgets (in SI units, not dB) are essentially of the form of

$$SINR = \frac{P}{L(N + I)}, \qquad (6)$$

where

$SINR$	= Signal to interference ratio for the link in a period of *activity*,
P	= TX power in a period of *activity*,
L	= Linkloss,
I	= *Average* RX interference on the link.
N	= Thermal Noise

To check for coverage, we set P to the maximum allowed link power and check that SINR meets requirements. In other words we examine the link assuming it is *active*. LTE frames are two dimensional (*time and frequency*) entities and the averaging is considered for both dimensions.

- *Coverage Evaluation* is affected by averaging, only because we use the average interference I in the link-budget.

- *Capacity Evaluation* is also done with average quantities. The capacity constraint is that the average resource (RBs) usage on each cell-carrier must not exceed the maximum limit.

Averages are calculated by scaling quantities (*i.e. powers transmitted and resources consumed*) by the *RE usage (%)* factors. One should remember that our snapshot contains no information about which REs are in use by a link. Only two things are known about each link:

- The power and resources required to service the link in a period of activity.
- The average interference and average resource consumption that the link produces.

1.3 WHY PRODUCE SNAPSHOTS?

The main purpose of a snapshot is to provide us with *measures of system load.* In particular, each snapshot provides:

- The total consumed DL transmission power of each cell.
- The total UL mean interference level (out-cell noise) on each cell.
- The total UL and DL throughput on each cell.
- The total resource usage on each cell.

By running many snapshots, values for these quantities are obtained for different spatial distributions of terminals which are further used to analyse the UL and DL coverage for the system. When using Inter-Cell Interference Coordination (ICIC) schemes, the system loads. i.e. '*Downlink Load*' and '*Mean UL Interference Levels*' are calculated for Cell Centre Users (CCU) and Cell Edge Users (CEU) as explained in respective sections.

2 FORMULAE

2.1 LIST OF PRINCIPAL SYMBOLS

A_p	Attenuation factor of the carrier p
D_k	Transmit power dynamic range of terminal k
$E_{J,p}^{DL\ total,tx}$	DL total average transmitted energy per frame for cell J and carrier p
$EiRP_{J,p}^{DLRS,tx}$	Effective isotropic Radiated Power of DLRS for cell J and carrier p
ε, $EPRE$	***E***nergy ***P***er ***R***esource ***E***lement
f_v^{low}, f_i^{low}	Start/low frequencies of victim (v) and interfering (i) carriers respectively
f_v^{high}, f_i^{high}	End/high frequencies of victim (v) and interfering (i) carriers respectively
$f_{J,k}^{NRA}$	Multi User Gain non-Rayleigh Adjustment for cell J at the location of terminal k
$G_J^{antenna}$	Attenna gain of cell J
$G_k^{antenna}$	Antenna gain of terminal k
$G_J^{DL\ corr}$	DL antenna correction gain of cell J
$G_J^{UL\ corr}$	UL antenna correction gain of cell J
G_J^{mha}	UL mast head amplifier gain of cell J
$G_k^{Rx\ Comb}$	DL receiver miscellaneous gains (combining gain, other gains) of terminal k
$G_{J,k}^{DL\ SINR}$	DL Beamforming SINR gain for served terminal k on cell J
$G_{J,k}^{DL\ Signal}$	DL Beamforming Signal Power Gain for served terminal k on cell J
$G_{C,k}^{DL\ Interf}$	DL Beamforming Interference Power Gain from cell C to victim terminal k
$G_{J,k}^{UL\ SINR}$	UL Beamforming SINR Gain for served terminal k on cell J
$g_{J,k}^{DL,\ SINR\,\&\,MIMO}$	DL Multi User Gain SINR & MIMO Dependence factor for terminal k of cell J
$g_{J,k}^{UL,\ SINR\,\&\,MIMO}$	UL Multi User Gain SINR & MIMO Dependence factor for terminal k of cell J
$g_J^{N-Users}$	Multi User Gain Number-of-Users Dependence factor for cell J
$I_{J,p,k}^{v\in V}$	DL received interference EPRE (general expression for any channel)
$I_{J,p,k}^{DLRS,tx}$	DL received interference EPRE from DLRS
$I_{J,p,k}^{BCH/SCH,tx}$	Combined DL received Interference EPRE from PBCH/P-SCH & S-SCH
$I_{J,p,k}^{CTRL,tx}$	DL received Interference EPRE from PDCCH

$I_{J,p,k}^{traffic,tx}$	DL received Interference EPRE from PDSCH
$I_{J,p,k}^{traffic/CTRL,tx}$	Combined DL received Interference EPRE from PDSCH/PDCCH
$I_{J,p}^{UL}$	UL received (inter-cell) Interference power for cell J and carrier p
K	Boltzmann constant (Joules/Kelvin)
L_J^{feeder}	Feeder loss, including feeder connector loss for cell J
L_J^{mha}	DL mast head amplifier (MHA) insertion loss for cell J
L_k^{body}	Body loss of terminal k
L_{Jk}^{DL}, L_{Jk}^{UL}	DL, UL linkloss between cell J and terminal k
$L_{Jk}^{pathloss}$	Pathloss between between cell J and terminal k
$L_{Jk}^{antenna}$	Antenna masking loss between cell J and terminal k
M	Modulation index. (1,2,4,6,7,8) for (BPSK,QPSK,16QAM,64QAM,128QAM,256QAM)
MUG_k^{DL},MUG_k^{UL}	DL, UL Multi User Gain for terminal k
$n^{slots/subframe}$	Number of slots per subframe
$n_p^{DL\,subframes}$	Number of available DL subframes for carrier p
$n_p^{UL\,subframes}$	Number of available UL subframes for carrier p
$n_p^{DL\,symbols/slot}$	Number of DL symbols per slot for carrier p
$n_p^{UL\,symbols/slot}$	Number of UL symbols per slot for carrier p
$n_p^{DL\,SC/RB}$	Number of DL subcarriers per RB for carrier p
$n_p^{DLRS\,SC/RB}$	Number of DLRS subcarriers per RB for carrier p for $tx = 1$
$n_p^{UL\,SC/RB}$	Number of UL subcarriers per RB for carrier p
n_p^{RB}	Number of available RBs for carrier p
$n_p^{CH\,subframes}$	Number of subframes where channel '*CH*' exists (*time domain of an LTE frame*)
$n_p^{CH\,RB}$	Number of RBs where channel '*CH*' exists (*frequency domain of an LTE frame*)
n_J^{BF}	Number of beamforming array elements on cell J
$N_{p,k}^{DL}$	DL thermal noise power for terminal k over the whole DL bandwidth of carrier p
$N_{p,k}^{DL\,RE}$	DL thermal noise power per resource element
$\overline{N}_{p,k}^{DL\,RE}$	DL thermal noise EPRE

$N_{J,p}^{UL}$	UL thermal noise power (over whole UL bandwidth)
$OH^{DL\ service}$	DL service rate overhead
$OH^{UL\ service}$	UL service rate overhead
$OH_{J,TTI\ Bundling}^{DL\ service}$	DL service rate overhead due to TTI Bundling for serving cell *J*
$OH_{J,TTI\ Bundling}^{UL\ service}$	UL service rate overhead due to TTI Bundling for serving cell *J*
O_{pq}^{freq}	Frequency-overlap factor for victim carrier *p*, and aggressor carrier *q*.
$O_{A\in C\to V\in J}^{time}$	Time-overlap factor for victim subframe *V* on cell *J*, and aggressor subframe *A* on cell *C*.
$O_{a\in A\to v\in V}^{element}$	Element-overlap factor for victim element *v* in subframe *V*, and aggressor element *a* in subframe *A*.
PPRE	Power Per Resource Element
P_J^{max}	Maximum transmission Power of cell *J*
$P_{J,p}^{DLRS,tx}$	Instantaneous DLRS Power for antenna configurations $tx = 1, 2\ \&\ > 2$
$P_{J,p}^{BCH,tx}$	Instantaneous PBCH Power for antenna configurations $tx = 1, 2\ \&\ > 2$
$P_{J,p}^{SCH\kappa,tx}$	Instantaneous P-SCH+S-SCH Power for antenna configurations $tx = 1, 2\ \&\ > 2$
$P_{J,p}^{CTRL,tx}$	Average PDCCH Power for antenna configurations $tx = 1, 2\ \&\ > 2$
$P_{J,p}^{traffic,tx}$	Average PDSCH Power for antenna configurations $tx = 1, 2\ \&\ > 2$
$P_{J,p,k}^{DL\ total,tx}$	Total DL received Power used in the RSSI calculations
P_k^{max}	Max TX Power of terminal k
P_k^{min}	Minimum TX Power of terminal k. $P_k^{min} = P_k^{max} / D_k$
$P_{p.k}^{req}$	UL required TX Power of terminal k
$P_{p,k}^{PC}$	Power controlled TX Power of terminal k. $P_{p,k}^{PC} = \max(P_k^{min}, P_{p.k}^{req})$
$\overrightarrow{Q_{J,k}}$	Quantized steering vector for cell J and terminal k. (See Beamforming)
$RE_p^{CH\ subframe,tx}$	REs per subframe of channel '*CH*' for antenna configurations $tx = 1, 2, > 2$
$RE_p^{CH,tx}$	Total REs of a channel/signal '*CH*' for antenna configurations $tx = 1, 2\ \&\ > 2$
$RE_p^{DLRS,tx}$	Total REs of DLRS for antenna configurations $tx = 1, 2\ \&\ > 2$
$RE_p^{CTRL,tx}$	Total REs of DL PDCCH, PCFICH & PHICH for antenna configurations $tx = 1, 2\ \&\ > 2$
$RE_p^{BCH,tx}$	Total REs of DL PBCH for antenna configurations $tx = 1, 2\ \&\ > 2$
$RE_p^{SCH,tx}$	Total REs of DL P-SCH & S-SCH for antenna configurations $tx = 1, 2\ \&\ > 2$

RE_p^{PUCCH}	Total REs of UL PUCCH
RE_p^{Sound}	Total REs of UL S-RS
RE_p^{Demod}	Total REs of UL DM-RS
$RE_p^{DL\,OH,tx}$	Total DL REs overhead for antenna configurations $tx = 1, 2 \;\&\; > 2$ and carrier p
$RE_p^{UL\,OH}$	Total UL REs overhead for carrier p
$RE_p^{DL\,total}$	Total DL REs for carrier p
$RE_p^{UL\,total}$	Total UL REs for carrier p
$RE_p^{DL\,traffic,tx}$	DL Traffic (PDSCH) REs for carrier p with antenna configurations $tx = 1, 2 \;\&\; > 2$
$RE_p^{UL\,traffic}$	UL Traffic (PUSCH) REs for carrier p
$R_p^{DL\,bearer,tx}$	DL bearer Rate for carrier p
$R_p^{UL\,bearer}$	UL bearer Rate for carrier p
$R_{min}^{DL\,service}$	Minimum-GBR DL service Rate
$R_{max}^{DL\,service}$	Maximum-MBR DL service Rate
$R_{min}^{UL\,service}$	Minimum-GBR UL service Rate
$R_{max}^{UL\,service}$	Maximum-MBR UL service Rate
$R_{J,Physical\,layer}^{service}$	Service Rate at Physical layer for cell J
R^{coding}	Coding Rate
$\boldsymbol{R_{J,k}^{DL}}$	DL TX Power Matrix for served terminal k on cell J. (See Beamforming)
$\boldsymbol{R_J^{DL}}$	Total DL TX Power Matrix for cell J. (See Beamforming)
$\boldsymbol{R_{J,k}^{UL}}$	UL RX Power Matrix for cell J and terminal k. (See Beamforming)
$\boldsymbol{R_J^{UL}}$	Total UL Noise and Interference Matrix for cell J. (See Beamforming)
$\overrightarrow{S_{J,k}}$	Steering vector for cell J and terminal k. (See Beamforming)
$SINR_{req}^{UL\,bearer}$	Required $SINR$ of UL bearer
$SINR_{req}^{DL\,bearer}$	Required $SINR$ of DL bearer
T	Temperature in Kelvin (for thermal noise calculation)
T_p^{frame}	Total frame duration for carrier p
$T_p^{DL\,frame}$	Total DL frame duration for carrier p

$T_p^{UL\,frame}$	Total UL frame duration for carrier p
$T_p^{useful\,DL\,frame}$	Useful DL frame duration for carrier p, (excluding time used for cyclic prefix)
$T_p^{useful\,UL\,frame}$	Useful UL frame duration for carrier p, (excluding time used for cyclic prefix)
$T_p^{useful\,symbol}$	Useful OFDMA symbol duration, excluding the cyclic prefix (CP)
$T_p^{full\,symbol}$	Total OFDMA symbol duration, including the cyclic prefix (CP)
T_p^{CP}	CP duration
U_J	Mean load of cell J
U_J^{CC}	Mean Cell Centre load of cell J
U_J^{CE}	Mean Cell Edge load of cell J
$\overrightarrow{w_{J,k}}^*$	Signal weights vector for served terminal k on cell J. (See Beamforming)
W_p	Bandwidth of carrier p
W_p^{UL}	Total UL Bandwidth of carrier p
W_p^{DL}	Total DL Bandwidth of carrier p
W_p^{DLRS}	Bandwdith occupied by DLRS. Used in DLRS thermal noise calculations
α	Resource consumption defined as $\alpha = \frac{Service\ Rate}{Bearer\ Rate}$
$\alpha_{p,min}^{DL\,bearer,tx}$	Min DL resource consumption of a bearer for antenna configurations $tx = 1, 2\ \&\ > 2$
$\alpha_{p,max}^{DL\,bearer,tx}$	Max DL resource consumption of a bearer for antenna configurations $tx = 1, 2\ \&\ > 2$
$\alpha_{p,min}^{UL\,bearer}$	Minimum UL resource consumption of a bearer
$\alpha_{p,max}^{UL\,bearer}$	Maximum UL resource consumption of a bearer
δ_J^{BCH}	EPRE offset for PBCH of cell J
δ_J^{SCH}	EPRE offset for P-SCH & S-SCH of cell J
δ_J^{CTRL}	EPRE offset for PDCCH of cell J
$\delta_J^{traffic}$	EPRE offset for PDSCH of cell J
$\delta_J^{MBSFN\,RS}$	EPRE offset for MBSFN RS for cell J
$\delta_J^{MBSFN\,DATA}$	EPRE offset for MBSFN DATA (MTCH) for cell J
$\delta_J^{MBSFN\,CTRL}$	EPRE offset for MBSFN CTRL (MCCH) for cell J
$\varepsilon_{J,p}^{DLRS,tx}$	EPRE of DLRS for cell J and carrier p

$\varepsilon_{J,p}^{BCH,tx}$	EPRE of PBCH for cell J and carrier p
$\varepsilon_{J,p}^{SCH,tx}$	EPRE of P-SCH & S-SCH for cell J and carrier p
$\varepsilon_{J,p}^{BCH/SCH,tx}$	Combined EPRE of PBCH, P-SCH & S-SCH for cell J and carrier p
$\varepsilon_{J,p}^{CTRL,tx}$	EPRE of PDCCH for cell J and carrier p at full DL load
$\varepsilon_{J,p}^{traffic,tx}$	EPRE of PDSCH for cell J and carrier p at full DL load
$\varepsilon_{J,p}^{traffic/CTRL,tx}$	Combined EPRE of PDSCH/PDCCH channels at full DL load
$\varepsilon_{J,p}^{MBSFN\ RS}$	EPRE of MBSFN RS for cell J and carrier p
$\varepsilon_{J,p}^{MBSFN\ DATA}$	EPRE of MBSFN DATA (MTCH) for cell J and carrier p
$\varepsilon_{J,p}^{MBSFN\ CTRL}$	EPRE of MBSFN CTRL (MCCH) for cell J and carrier p
$\eta_{p,k}$	Thermal noise figure of terminal k
$\eta_{J,p}$	Thermal noise figure of cell J
$(\Delta f)_p$	Subcarrier spacing used by carrier p
Δ_k	Beamwidth of the terminal antenna
Θ_{JC}^{ICIC}	Inter-Cell Interference Coordination (ICIC) scale factor for interference
φ_p^{CF}	ICIC coordination factor for carrier p

2.2 NOTATION

Symbols in subsequent sections use the following notation.

$\sum_{p}$ indicates a sum over all carriers *p*.

$\sum_{J}$ indicates a sum over all cells *J*.

$\sum_{k}$ indicates a sum over all terminals *k*.

$\sum_{k \in J}$ indicates a sum over all terminals *k* in cell *J*.

Unless stated otherwise, all quantities and formulae are in standard SI units, not in dB.

2.3 CELLS USING ABS OR MBSFN

All the basic DL EPRE values described in this document (and seen in the tool GUI) refer to a cell that has no multicast subframes and no ABS (Almost Blank Subframes). If a cell is configured to use ABS and/or MBSFN then the EPRE values on the cell are not affected. What changes is how the EPRE values are used in calculations for different DL subframe types. The following table shows where the DL EPRE values are relevant.

DL Subframe Type	**Relevant EPREs for cell *J* with carrier *p***
Unicast (non-ABS)	$\varepsilon_{J,p}^{DLRS,tx}$, $\varepsilon_{J,p}^{BCH,tx}$, $\varepsilon_{J,p}^{SCH,tx}$, $\varepsilon_{J,p}^{CTRL,tx}$, $\varepsilon_{J,p}^{traffic,tx}$
Unicast (ABS)	$\varepsilon_{J,p}^{DLRS,tx}$
Multicast Data (MBSFN part of subframe)	$\varepsilon_{J,p}^{MBSFN\ RS}$, $\varepsilon_{J,p}^{MBSFN\ DATA}$
Multicast Ctrl (MBSFN part of subframe)	$\varepsilon_{J,p}^{MBSFN\ RS}$, $\varepsilon_{J,p}^{MBSFN\ CTRL}$
Multicast (non-MBSFN part of subframe)	$\varepsilon_{J,p}^{DLRS,tx}$, $\varepsilon_{J,p}^{CTRL,tx}$

When ABS is specified on a cell, the DL cell load refers only to the DL subframes that can carry unicast traffic (i.e. DL non-ABS subframes). So a DL load of 100% means that all the DL non-ABS subframes are fully used, and the cell has reached capacity. Similarly, the measure of UL noise rise on a cell refers only to the UL unicast non-ABS subframes since only these subframes carry UL traffic.

2.4 MBSFN AREA DEFINITIONS

The following parameters determine the subframes used for an MBSFN area.

Repetition Period (in frames): {1, 2, 4, 8, 16, 32}
Offset (in frames): {0, … , 7}
Pattern Size (in frames): {1 or 4}
Pattern (6 bits or 24 bits according to pattern size):

A 24 bit pattern refers to 4 consecutive frames.
Each block of 6 bits corresponds to particular subframes (numbered 0, …, 9) within a frame.
FDD: The 6 bits correspond to subframes (1, 2, 3, 6, 7, 8).
e.g. 100100 designates subframes 1 and 6.
TDD: The top 5 bits correspond to subframes (3, 4, 7, 8, 9). The 6th bit is always 0.
e.g. 101000 designates subframes 3 and 7.

The following parameters determine the subframes used by the MBSFN Ctrl channel (MCCH) for an MBSFN area. They must be a subset of the subframes mentioned above, or else the MBSFN area configuration will be invalid.

MCCH Repetition Period (in frames): {32, 64, 128, 256}
MCCH Offset (in frames): {0, … , 10}
MCCH Pattern: (6 bits):

The 6 bits correspond to particular subframes (numbered 0, …, 9) within a frame.
FDD: The 6 bits correspond to subframes (1, 2, 3, 6, 7, 8).
e.g. 100100 designates subframes 1 and 6.
TDD: The top 5 bits correspond to subframes (3, 4, 7, 8, 9). The 6th bit is always 0.
e.g. 101000 designates subframes 3 and 7.

2.4.1 Example MBSFN area configuration for an FDD carrier

Repetition Period: 2
Offset: 1
Pattern Size: 1
Pattern: 011001
MCCH Repetition Period: 32
MCCH Offset: 5
MCCH Pattern: 010000

The Offset of 1 and repetition of 2 results in system frame numbers (SFN) 1, 3, 5, 7, etc.
The MCCH Offset of 5 and repetition of 32 results in system frame numbers (SFN) 5, 37, 69, etc.

Indicating regular unicast subframes with "`-`", MCCH subframes with "`C`", and MTCH (MBSFN Data Channel) subframes with "`T`" we then have the following subframe pattern.

```
   SFN0        SFN1        SFN2        SFN3
----------  --TT----T-  ----------  --TT----T-

   SFN4        SFN5        SFN6        SFN7
----------  --CT----T-  ----------  --TT----T-

   SFN8        SFN9        SFN10       SFN11
----------  --TT----T-  ----------  --TT----T-
```

etc.

Each MBSFN subframe may have a non-MBSFN region consisting of the first 1 or two symbols in the subframe. These symbols have the same cyclic prefix as the non-MBSFN (unicast) subframes, so there may be a gap between the non-MBSFN symbols and the MBSFN symbols.

2.4.2 Assigning multiple MBSFN areas to a cell

When assigning multiple MBSFN areas to a cell, the pattern of subframes must not overlap because each subframe can only be used by a single MBSFN area. If the user assigns MBSFN areas to cell and any of those areas have overlapping subframes, then the simulator will disable MBSFN on that cell.

2.5 MBSFN Area Rate calculation

2.5.1 Mean number of MBSFN subframes per Frame

$$n_p^{MBSFN} = \frac{n_p^{MBSFN\ pattern\ subframes}}{n_p^{MBSFN\ period}}, \tag{7}$$

where

$n_p^{MBSFN\ pattern\ subframes}$ is the number of '1's in the subframe pattern.

$n_p^{MBSFN\ period}$ is the repetition period (in frames).

2.5.2 Mean number of MBSFN Ctrl subframes per Frame

$$n_p^{MCCH} = \frac{n_p^{MCCH\ pattern\ subframes}}{n_p^{MCCH\ period}} \tag{8}$$

where

$n_p^{MCCH\ pattern\ subframes}$ is the number of '1's in the MCCH subframe pattern.

$n_p^{MCCH\ period}$ is the MCCH repetion period (in frames).

2.5.3 Mean number of MBSFN Data subframes per Frame

$$n_p^{MTCH} = n_p^{MBSFN} - n_p^{MCCH} \tag{9}$$

2.5.4 Mean number of MBSFN RS REs per Frame

$$RE_p^{MBSFN\ RS} = n_p^{MBSFN}\ n^{slots/subframe}\ n_p^{MBSFN\ symbols/slot}\ n_p^{RB}\ n_p^{DL\ SC/RB} \cdot \frac{\alpha_p^{RS}}{8} \tag{10}$$

2.5.5 Mean number of MBSFN Ctrl REs per Frame

$$RE_p^{MBSFN\ CTRL} = n_p^{MCCH}\ n^{slots/subframe}\ n_p^{MBSFN\ symbols/slot}\ n_p^{RB}\ n_p^{DL\ SC/RB} \cdot \frac{7\alpha_p^{non-RS}}{8} \tag{11}$$

2.5.6 Mean number of MBSFN Data REs per Frame

$$RE_p^{MBSFN\ DATA} = n_p^{MTCH}\ n^{slots/subframe}\ n_p^{MBSFN\ symbols/slot}\ n_p^{RB}\ n_p^{DL\ SC/RB} \cdot \frac{7\alpha_p^{non-RS}}{8} \quad (12)$$

where

$n_p^{MBSFN\ symbols/slot}$ is 6 for 15 kHz subcarriers, and 3 for 7.5 kHz subcarriers.

n_p^{RB} is the number of physical RB per carrier.

$n_p^{DL\ SC/RB}$ is the number of DL subcarriers per RB.

α_p^{RS} is a correction factor for MBSFN RS elements lost due to the non-MBSFN region in MBSFN subframes.

α_p^{non-RS} is a correction factor for MBSFN non-RS elements lost due to the non-MBSFN region in MBSFN subframes.

α_p^{RS}	**Sub Carrier**	**Non-MBSFN Region Length**		
		0	**1**	**2**
	15kHz	1	1	1
	7.5kHz	1	1	2/3

α_p^{non-RS}	**Sub Carrier**	**Non-MBSFN Region Length**		
		0	**1**	**2**
	15kHz	1	19/21	17/21
	7.5kHz	1	17/21	14/21

2.5.7 MBSFN Area Data Rate

$$R_p^{MBSFN} = \frac{RE_p^{MBSFN\ DATA} \cdot M \cdot R^{coding}}{T_p^{frame}} \quad (13)$$

where $R_p^{MBSFN\ Bearer}$ is the MBSFN Area Data Rate. M and R^{coding} are the bearer modulation index and channel coding rate of the data bearer assigned to the MBSFN area, and T_p^{frame} is the frame duration.

2.6 Signalling and Control Channels Overhead

Signalling and Control channel overheads for a given TDD / FDD carrier p are calculated by using the ‘RE per Subframe’, ‘# of Subframes’ and ‘# of Resource Blocks’ defined on the ‘Overhead’ page of LTE Carriers as shown in Fig. 1 and can be expressed as

$$RE_p^{CH,tx} = RE_p^{CH\ subframe,tx}\ n_p^{CH\ subframes}\ n_p^{CH\ RB}\ , \tag{14}$$

where $RE_p^{CH,tx}$ are the total resource elements (REs) dedicated for a specific DL or UL channel/signal for antenna configurations $tx = 1, 2$ and > 2 in (14).

Note that for UL channels/signals the number of transmit elements does not affect overheads.

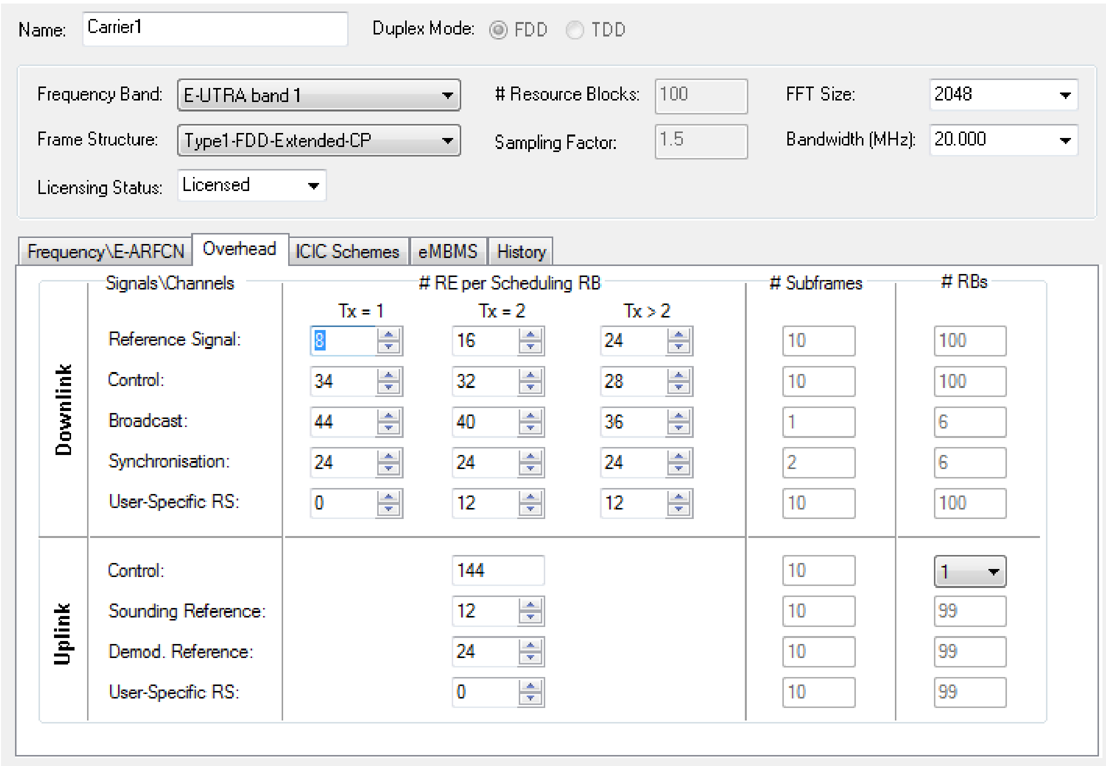


Figure 1: Signals and Control Channel Overheads

Downlink

DL Reference Signal

$$RE_p^{DLRS,tx} = RE_p^{DLRS\ subframe,tx}\ n_p^{DLRS\ subframes}\ n_p^{DLRS\ RB}\ , \tag{15}$$

where $RE_p^{DLRS,tx}$ are the total REs for DL Reference Signal (DLRS) for antenna configurations $tx = 1, 2$ and > 2.

The number of REs used for DLRS depend on the transmit antennas employed by the cell J. For the subcarrier spacing of 15 *kHz*, each scheduling resource block (SRB) (*of dimensions: 12 subcarriers in frequency domain and 2 slots i.e. 1 subframe in time domain*), carries 8, 16 and 24 DLRS REs for $tx = 1, 2$ and 4 respectively.

For subcarrier spacing of 15 *kHz* and $tx = 1$, DLRS symbols exist within the 1st and the 3rd last OFDM symbols of each slot and with a frequency-domain spacing of six subcarriers. Furthermore, there is a frequency-domain staggering of three subcarriers between the 1st and 2nd reference symbols. Hence, within each subframe (*i.e. 12 subcarriers and 2 slots*), there are 8 reference symbols. This can be visualized in Fig. 2 which shows a LTE DL FDD frame structure.

DL Control Channels

$$RE_p^{CTRL,tx} = RE_p^{CTRL\ subframe,tx}\ n_p^{CTRL\ subframes}\ n_p^{CTRL\ RB}, \tag{16}$$

where $RE_p^{CTRL,tx}$ are the total resource elements for DL control channels (PDCCH, PCFICH and PHICH) for antenna configurations $tx = 1, 2$ and > 2.

The PCFICH carriers the information about the number of OFDM symbols allocated for PDCCH in each subframe whereas PHICH carries the Hybrid ARQ ACK/NAKs in response to uplink transmission. PDCCH is transmitted in the first n OFDM symbols of each subframe, where $n \le 3$. However, REs reserved for DLRS cannot be used by PDCCH, e.g. considering $n = 3$ and with the subcarrier spacing of 15 *kHz (also depicted in Fig. 2)*, 34 out of 36 REs are used for PDCCH as 2 REs in the 1st OFDM symbol of each subframe are reserved for the DLRS.

DL Broadcast Channel

$$RE_p^{BCH,tx} = RE_p^{BCH\ subframe,tx}\ n_p^{BCH\ subframes}\ n_p^{BCH\ RB}\ , \tag{17}$$

where $RE_p^{BCH,tx}$ are the total resource elements for DL broadcast channel (PBCH) for antenna configurations $tx = 1, 2$ and > 2.

The PBCH is transmitted on 4 OFDM symbols in the 1st downlink subframe spanning over the central 6 RBs (*which corresponds to the minimum possible LTE system bandwidth i.e. 1.4MHz*).This ensures detectability without the UE/Terminal having the prior knowledge of the whole system bandwidth. REs reserved for DLRS cannot be used by PBCH as shown in Fig. 2.

DL Synchronization Channel

$$RE_p^{SCH,tx} = RE_p^{SCH\ subframe,tx}\ n_p^{SCH\ subframes}\ n_p^{SCH\ RB}\ , \tag{18}$$

where $RE_p^{SCH,tx}$ are the total resource elements for DL synchronisation channel (P-SCH and S-SCH) for antenna configurations $tx = 1, 2$ and > 2.

Similar to PBCH, the P-SCH and S-SCH are transmitted using a single OFDM symbol each, in the 1st and 6th downlink subframe spanning over the central 6 RBs. P-SCH and S-SCH REs do not overlap the REs reserved for DLRS thereby each frame (*based on the 15 kHz subcarrier spacing*) employs a total of 288 P-SCH and S-SCH REs (i.e. 24 REs per SRB) for $tx = 1, 2$ and 4 respectively.

DL UE-Specific RS

This overhead only applies to the resource blocks allocated to terminals that are served using DL Beamforming. Since each of these resource blocks will have fewer traffic REs, the overall RE consumption for the beamformed connection will be larger than the non-beamformed case. This DL overhead only has an effect within the simulation checks for DL capacity and DL resource consumption.

Total DL Overhead

$$RE_p^{DL\ OH,tx} = RE_p^{DLRS,tx} + RE_p^{CTRL,tx} + RE_p^{BCH,tx} + RE_p^{SCH,tx}, \quad \textbf{(19)}$$

where $RE_p^{DL\ OH,tx}$ are the DL overhead REs for a FDD/TDD carrier p.

Uplink

UL Control Channel

$$RE_p^{PUCCH} = RE_p^{PUCCH\ subframe}\ n_p^{PUCCH\ subframes} n_p^{PUCCH\ RB}\ , \quad \textbf{(20)}$$

where RE_p^{PUCCH} are the total resource elements for physical uplink control channel (PUCCH).

The PUCCH is transmitted in a frequency region on the edges of the system bandwidth and each PUCCH transmission in one subframe is comprised of single PRB at or near one edge of the system bandwidth followed by a second PRB at or near the opposite edge of the system bandwidth; together the two PRB are referred to as a PUCCH region. The number of PUCCH regions depends on the system bandwidth, e.g. the typical values for these regions are 1, 2, 4, 8 and 16 for bandwidths of 1.4, 3, 5, 10 and 20 MHz respectively. In Fig 3, an LTE UL FDD frame has been shown with 2 PUCCH regions ($m = 0, 1$) arranged at the edges of the bandwidth. PUCCH overhead in term of '# of Resource blocks' can be defined on the Overhead page of LTE carriers as shown in Fig.1.

UL Sounding Reference Signal

$$RE_p^{Sound} = RE_p^{Sound\ subframe}\ n_p^{Sound\ subframes} n_p^{Sound\ RB}\ , \quad \textbf{(21)}$$

where RE_p^{Sound} are the total resource elements for UL Sounding Reference Signal (S-RS).

The S-RS is used for channel quality determination for the frequency-selective scheduling on the UL and transmitted on 1 OFDM symbol in each UL subframe as shown in Fig. 3.

UL Demodulation Reference Signal

$$RE_p^{Demod} = RE_p^{Demod\ subframe}\ n_p^{Demod\ subframes} n_p^{Demod\ RB}\ , \quad \textbf{(22)}$$

where RE_p^{Demod} are the total resource elements for UL Demodulation Reference Signal (DM-RS).

The DM-RS is associated with the transmission of UL data on the Physical UL Shared Channel PUSCH and/or control signalling on the PUCCH; primarily used for channel estimation for coherent demodulation. It is transmitted on 2 OFDM symbols and for a given user/terminal occupies the same bandwidth as its PUSCH/PUCCH data transmission.

UL UE-Specific RS

This overhead only applies to the resource blocks allocated to terminals that are served using UL Beamforming. Since each of these resource blocks will have fewer traffic REs, the overall RE consumption for the beamformed connection will be larger than the non-beamformed case. This UL overhead only has an effect within the simulation checks for UL capacity and UL resource consumption.

Total UL Overhead

$$RE_p^{UL\ OH} = RE_p^{PUCCH} + RE_p^{Sound} + RE_p^{Demod}\ , \quad \textbf{(23)}$$

Figure 2: FDD DL frame structure (tx =1)

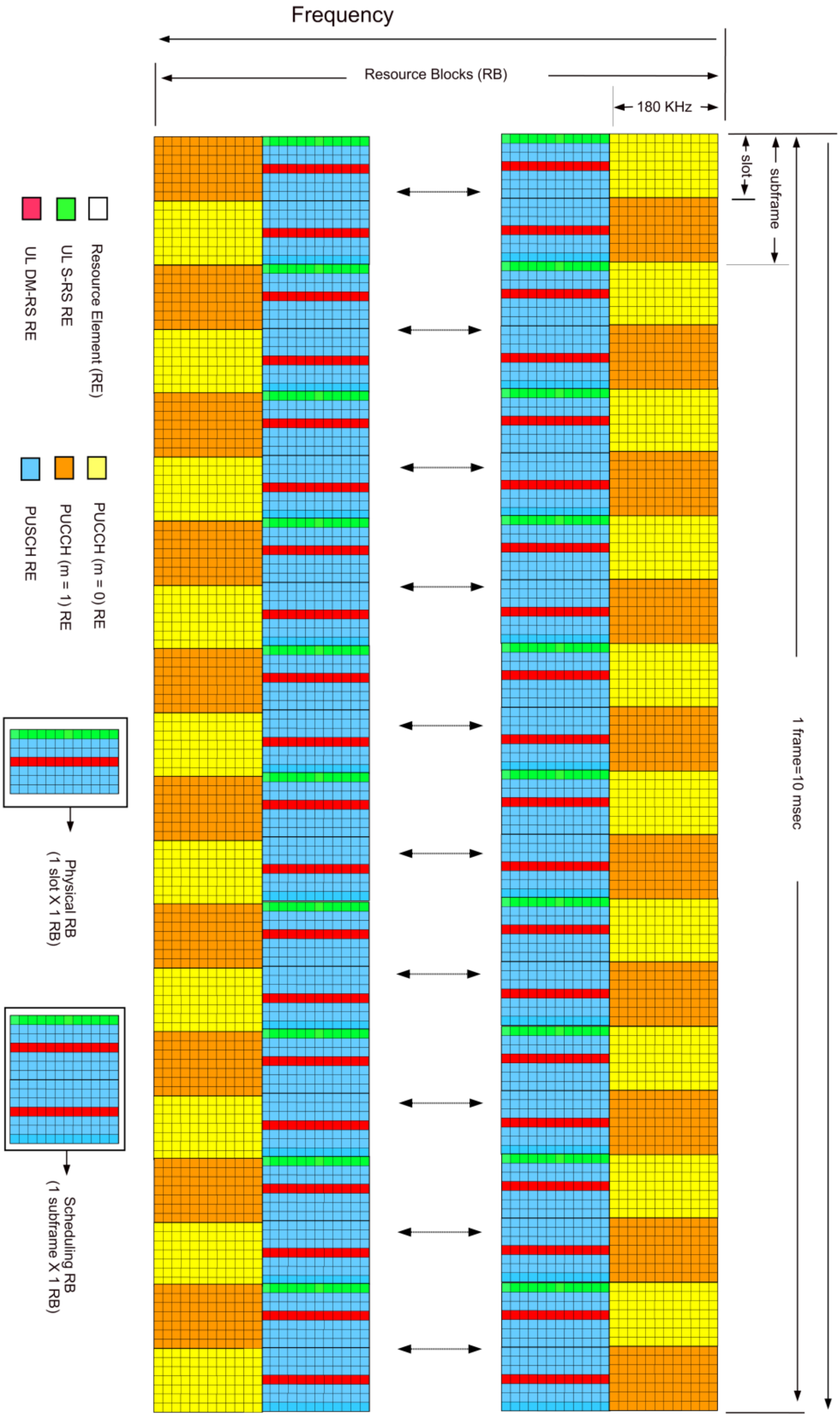


Figure 3: FDD UL frame structure

2.7 Available Resources (Total and Traffic)

Downlink

Total DL Resource Elements

$$RE_p^{DL\ total} = n_p^{DL\ subframes}\ n^{slots/subframe}\ n_p^{DL\ symbols/slot} \cdot n_p^{RB}\ n_p^{DL\ SC/RB}, \quad \textbf{(24)}$$

where $RE_p^{DL\ total}$ are the total DL REs for a given FDD/TDD carrier p. $n_p^{DL\ subframes}$ is the number of available DL subframes. For FDD frame structures, $n_p^{DL\ subframes} = 10$. For TDD frame structures $n_p^{DL\ subframes}$ depends on the TDD 'Frame Configuration' defined on the 'General' page of TDD frame structure parameters.

DL Traffic Resource Elements

$$RE_p^{DL\ traffic,tx} = RE_p^{DL\ total} - RE_p^{DL\ OH,tx}\ , \quad \textbf{(25)}$$

where $RE_p^{DL\ traffic,tx}$ are the DL traffic REs for a given FDD/TDD carrier p for $tx = 1, 2$ and 4. $RE_p^{DL\ total}$ and $RE_p^{DL\ OH,tx}$ are calculated as per (24) and (19) respectively.

Uplink

Total UL Resource Elements

$$RE_p^{UL\ total} = n_p^{UL\ subframes}\ n_p^{slots/subframe}\ n_p^{UL\ symbols/slot} \cdot n_p^{RB} n_p^{UL\ SC/RB}, \quad \textbf{(26)}$$

where $RE_p^{UL\ total}$ are the total UL REs for a given FDD/TDD carrier p. $n_p^{UL\ subframes}$ is the number of available UL subframes. For FDD frame structures, $n_p^{UL\ subframes} = 10$. For TDD frame structures, $n_p^{UL\ subframes}$ depends on the TDD 'Frame Configuration' defined on the 'General' page of TDD frame structure parameters.

UL Traffic Resource Elements

$$RE_p^{UL\ traffic} = RE_p^{UL\ total} - RE_p^{UL\ OH}, \quad \textbf{(27)}$$

where $RE_p^{UL\ traffic}$ are the UL traffic REs for a given FDD/TDD carrier p. $RE_p^{UL\ total}$ and $RE_p^{UL\ OH}$ are calculated as per (26) and (23) respectively .

2.8 BEARER RATES AND RESOURCE CONSUMPTION

The measures of system load depend on the resource consumption/usage of the frame. In Fig. 4 a simplified LTE DL frame is shown where the frame usage or the RE consumption is defined as $\alpha\beta$. Time factor β is the time duration of the resource consumption relative to the total time domain resources (OFDM Symbols) of a single link in the DL while α is the frequency domain factor and represents the consumption of frequency domain resources relative to the total frequency domain resource in the DL. Same definitions can be applied to the UL

Resource consumption is defined as the ratio of the required service rate (*Minimum-GBR and Maximum-MBR*) and the maximum available bearer rate calculated by using the employed modulation and channel coding rate.

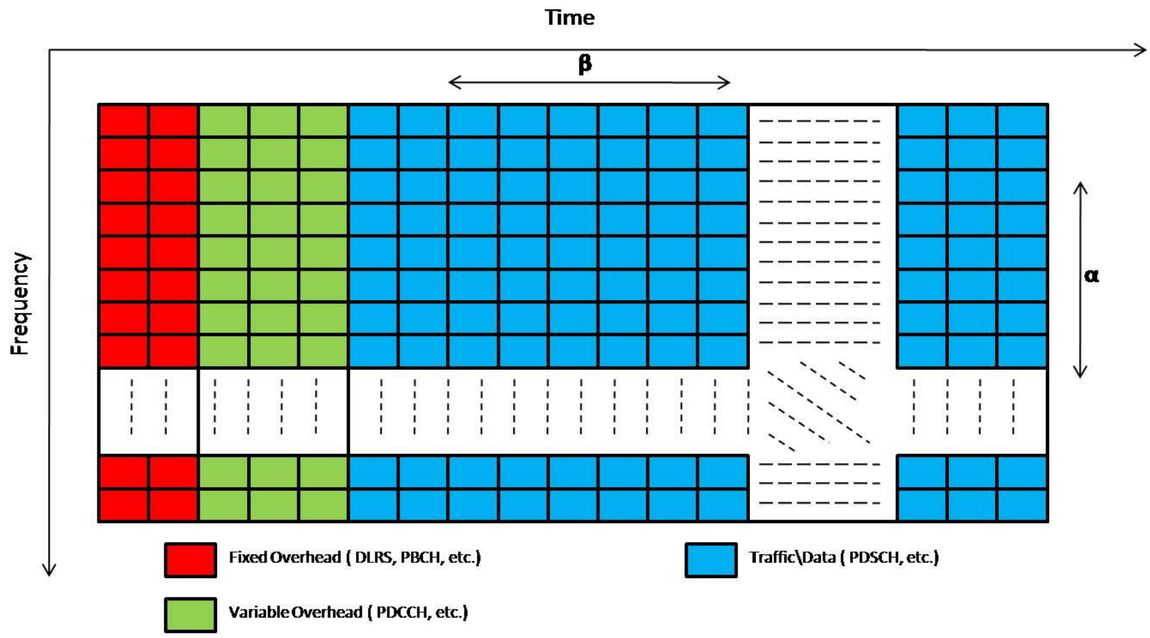


Figure 4: Simplified frame structure for modelling of Resource consumption

To model the average interference effects in the network without the exact knowledge of the time-frequency PRBs assigned to a specific connection, a simplification can be by made by reducing the two dimensional (time-frequency) frame into a single dimensional value of resource usage, either in the frequency domain or the time domain. Considering the time factor $= 1$, the simplified resource consumption (*RE Usage*) can then be defined as

$$\beta = 1\,, \qquad \alpha = \frac{Service\ Rate\ at\ Physical\ layer}{Bearer\ Rate}\,. \tag{28}$$

The service rate requirements, $R^{service}$, are specified at application layer. The resource consumption is occuring at the physical layer and is therefore calculated based on the service rate at physical layer that is accounting for the applicable overheads:

$$R^{service}_{J,Physical\ layer} = R^{service}(1 + OH^{service})\,(1 + OH^{service}_{J,TTI\ Bundling}) \tag{29}$$

where $R^{service}_{J,Physical\ layer}$ is the service rate at physical layer for cell J. $OH^{service}$ is the service rate overhead and $OH^{DL\ service}_{J,TTI\ Bundling}$ is the service rate overhead due to TTI bundling for cell J. If cell J does not support TTI bundling, then $OH^{service}_{J,TTI\ Bundling} = 0$.

Downlink

DL Bearer Rate

$$R_p^{DL\ bearer,tx} = RE_p^{DL\ traffic,tx} \cdot M \cdot R^{coding} \left(\frac{1}{T_p^{frame}}\right), \tag{30}$$

where $R_p^{DL\ bearer,tx}$ is the DL bearer rate for a given FDD/TDD carrier p. $RE_p^{DL\ traffic,tx}$ are the DL traffic REs for a given FDD/TDD carrier p for $tx = 1, 2$ and 4, calculated as per (25). M and R^{coding} are the bearer modulation index and channel coding rate respectively. T_p^{frame} is the frame duration.

DL Resource Consumption

$$\alpha_{p,J,min}^{DL\ bearer,tx} = \frac{R_{min}^{DL\ service}\left(1 + OH^{DL\ service}\right)\left(1 + OH_{J,TTI\ Bundling}^{DL\ service}\right)}{R_p^{DL\ bearer,tx}}, \tag{31}$$

and

$$\alpha_{p,J,max}^{DL\ bearer,tx} = \frac{R_{max}^{DL\ service}\left(1 + OH^{DL\ service}\right)\left(1 + OH_{J,TTI\ Bundling}^{DL\ service}\right)}{R_p^{DL\ bearer,tx}}, \tag{32}$$

where $\alpha_{p,min}^{DL\ bearer,tx}$ and $\alpha_{p,max}^{DL\ bearer,tx}$ are the minimum and maximum resource consumption for a bearer configured for carrier p for cell J. $R_{min}^{DL\ service}$ and $R_{max}^{DL\ service}$ are Minimum-GBR and Maximum-MBR service rates. $OH^{DL\ service}$ is the DL service rate overhead and $R_p^{DL\ bearer,tx}$ is the DL bearer rate for a given FDD/TDD carrier p and calculated as per (30). $OH_{J,TTI\ Bundling}^{DL\ service}$ is the service rate overhead due to TTI bundling for cell J. If cell J does not support TTI bundling, then $OH_{J,TTI\ Bundling}^{DL\ service} = 0$.

Uplink

UL Bearer Rate

$$R_p^{UL\ bearer} = RE_p^{UL\ traffic} \cdot M \cdot R^{coding} \left(\frac{1}{T_p^{frame}}\right), \tag{33}$$

where $R_p^{UL\ bearer}$ is the UL bearer rate for a given FDD/TDD carrier p. $RE_p^{UL\ traffic}$ are the UL traffic REs for a given FDD/TDD carrier p, calculated as per (27). M and R^{coding} are the bearer modulation index and channel coding rate respectively. T_p^{frame} is the frame duration.

UL Resource Consumption

$$\alpha_{p,J,min}^{UL\ bearer} = \frac{R_{min}^{UL\ service}\left(1 + OH^{UL\ service}\right)\left(1 + OH_{J,TTI\ Bundling}^{UL\ service}\right)}{R_p^{UL\ bearer}}, \tag{34}$$

and

$$\alpha_{p,J,max}^{UL\ bearer} = \frac{R_{max}^{UL\ service}\left(1 + OH^{UL\ service}\right)\left(1 + OH_{J,TTI\ Bundling}^{UL\ service}\right)}{R_p^{UL\ bearer}}, \tag{35}$$

where $\alpha_{p,min}^{UL\,bearer}$ and $\alpha_{p,max}^{UL\,bearer}$ are the minimum and maximum resource consumption for a bearer configured for carrier p for cell J. $R_{min}^{UL\,service}$ and $R_{max}^{UL\,service}$ are the 'Minimum-GBR' and 'Maximum-MBR' service rates. $OH^{UL\,service}$ is the UL service rate overhead and $R_{p}^{UL\,bearer}$ is the UL bearer rate for a given FDD/TDD carrier p, calculated as per (33). $OH_{J,TTI\,Bundling}^{UL\,service}$ is the service rate overhead due to TTI bundling for cell J. If cell J does not support TTI bundling, then $OH_{J,TTI\,Bundling}^{UL\,service} = 0$.

2.8.1 Carrier Aggregation

During CA operation the terminal is served over mulitple different carriers over potentially different bearers. The sets of DL and UL aggregated carriers for the terminal can be diffreent. This results in a reduced effective resouce consumption for a bearer over the individual carriers that is given by:

$$\alpha_{effective,min}^{DL} = \frac{1}{\sum_p \frac{1}{\alpha_{p,min}^{DL\,bearer}}} \quad , \qquad \alpha_{effective,max}^{DL} = \frac{1}{\sum_p \frac{1}{\alpha_{p,max}^{DL\,bearer}}} \quad , \tag{36}$$

$$\alpha_{effective,min}^{UL} = \frac{1}{\sum_q \frac{1}{\alpha_{q,min}^{UL\,bearer}}} \quad , \qquad \alpha_{effective,max}^{UL} = \frac{1}{\sum_q \frac{1}{\alpha_{q,max}^{UL\,bearer}}} \quad , \tag{37}$$

where $\alpha_{effective,min}^{DL}$ and $\alpha_{effective,max}^{DL}$ are the minimum and maximum effective resource consumption for the selected DL bearers of the DL aggregated carriers p, and $\alpha_{effective,min}^{UL}$ and $\alpha_{effective,max}^{UL}$ are the minimum and maximum effective resource consumption for the selected UL bearers of the UL aggregated carriers q.

2.9 Overview of LTE Interference Modelling

Every cell transmits the DL physical channels using a particular set of REs and subframes. In order to properly calculate SINR for a physical channel, we must account for the fact that cells can have differing patterns of REs and subframes, and that this can give interference between different physical channels.

We consider a general situation when we have a terminal served by cell J using carrier p. We call this cell the "victim" since the signal that the terminal receives from this cell will be subject to interference. We need to calculate the received interference from an "aggressor" cell C using carrier q. To do this we will need to introduce the following factors which are described more fully in later sections.

- **The *frequency-overlap* factor for *power* :** $\left(\boldsymbol{O_{pq}^{freq}}\right)$

  If we have a power P_q across the aggressor bandwidth W_q, with P_p of this power affecting the victim bandwidth W_p, then these powers are related as follows

  $$P_p = O_{pq}^{freq} \cdot P_q \,. \tag{38}$$

  O_{pq}^{freq} can be thought of as the operator that maps *power* from the aggressor carrier bandwidth to the victim carrier bandwidth.

- **The *frequency-overlap* factor for *EPRE*:** $\left(\boldsymbol{O_{pq}^{freq} W_q / W_p}\right)$

  For LTE carriers we can express each power in (38) as a product of the carrier bandwidth and an EPRE (without CP) in that bandwidth. This is because EPRE (without CP) is just another name for power spectral density. So we have $P_p = W_p\,\varepsilon_p$ and $P_q = W_q\,\varepsilon_q$ which gives the following relation between EPRE values.

  $$\varepsilon_p = \left(O_{pq}^{freq}\, W_q / W_p\right) \cdot \varepsilon_q \,. \tag{39}$$

  $\left(O_{pq}^{freq}\, W_q / W_p\right)$ can be thought of as the operator that maps *EPRE* (without CP) from the aggressor carrier q to the victim carrier p. This overlap factor is required in formulas that express SINR as a ratio of received EPRE values rather than as a ratio of received powers.

- **The *time-overlap* factor:** $\left(\boldsymbol{O_{A\in C\to V\in J}^{time}}\right)$

  This considers the sequences of subframes on the two cells. It is the way we account for eICIC effects as well as interference between unicast and multicast subframes. It gives the average number of aggressor subframes of type A (on cell C) per victim subframe of type V (on cell J).

- **The *element-overlap* factor:** $\left(\boldsymbol{O_{a\in A\to v\in V}^{element}}\right)$

  This considers the patterns of REs within subframes. It is the way we account for interference between different DL physical channels. It gives the average number of aggressor REs of type a (in aggressor subframe type A) per victim RE of type v (in victim subframe type V).

2.10 Calculation of Frequency-Overlap Factors

Consider an interfering carrier i and a victim carrier v as shown in Fig. 5.

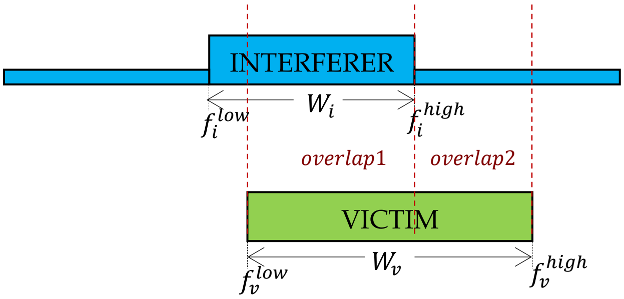


Figure 5: Illustration of overlapping carriers

For perfectly rectangular transmission and reception bandwidths, the overlapping bandwidth is given by

$$W_{vi}^{overlap1} = \max\left(0, \min\left(f_v^{high}, f_i^{high}\right) - \max\left(f_v^{low}, f_i^{low}\right)\right) \, . \quad (40)$$

We define the *overlap factor* as the proportion of the interfering carrier bandwidth that overlaps the victim carrier, as follows

$$O_{vi}^{overlap1} = W_{vi}^{overlap1} \;/\; W_i \, . \quad (41)$$

The interferer has attenuation factor A_i for interference transmitted on adjacent bandwidths (i.e. from $\{f_i^{low} - W_i\}$ to f_i^{low}, and f_i^{high} to $\{f_i^{high} + W_i\}$). The bandwidth overlap between the victim and these adjacent bandwidths is given by

$$\begin{aligned} W_{vi}^{overlap2} = &\max\left(0, \min\left(f_v^{high},\; f_i^{high} + W_i\right) \;-\; \max\left(f_v^{low},\; f_i^{high}\right)\right) \;+ \\ &\max\left(0, \min\left(f_v^{high},\; f_i^{low}\right) \;-\; \max\left(f_v^{low},\; f_i^{low} - W_i\right)\right) \, , \end{aligned} \quad (42)$$

and the corresponding overlap factor for these adjacent bandwidths becomes

$$O_{vi}^{overlap2} = W_{vi}^{overlap2} \;/\; W_i \, . \quad (43)$$

The combined overlap factor can then be expressed as

$$O_{vi}^{freq} = O_{vi}^{overlap1} \;+\; A_i O_{vi}^{overlap2} , \quad (44)$$

The frequency overlap factor O_{vi}^{freq} can be thought of as an operator that maps *power* from the aggressor carrier bandwidth to the victim carrier bandwidth.

If we need to map an *EPRE* value (without CP) from an aggressor carrier to a victim carrier then we need to use a slightly different frequency overlap factor. Consider the situation when we have a power P_i across the aggressor bandwidth W_i, with P_v of this power affecting the victim bandwidth W_v. The frequency overlap factor in (44) relates these two powers as follows

$$P_v = O_{vi}^{freq} \cdot P_i \, . \quad (45)$$

For LTE carriers we can express each power as a product of the carrier bandwidth and an EPRE (without CP) in that bandwidth. This is because EPRE (without CP) is just another name for power spectral density.

$$P_v = W_v \, \varepsilon_v \,, \tag{46}$$

and

$$P_i = W_i \, \varepsilon_i \,. \tag{47}$$

Substituting these into (45) gives this relation between EPRE values

$$\varepsilon_v = (O_{vi}^{freq} \, W_i \,/\, W_v) \cdot \varepsilon_i \,. \tag{48}$$

Therefore the operator that maps an EPRE ε_i in the aggressor to an EPRE ε_v in the victim is given by

$$O_{vi}^{freq} \, W_i \,/\, W_v \,. \tag{49}$$

2.11 Calculation of Time-Overlap Factors

The time-overlap factor $O_{A \in C \to V \in J}^{time}$ gives the average number of aggressor subframes of type A (on aggressor cell C) per victim subframe of type V (on victim cell J). This factor allows us to model eICIC effects as well as handle interference between unicast and multicast subframes.

2.11.1 Subframe Types

We label subframes as follows:

`S`	represents a special TDD subframe.
`D` and `U`	represent DL and UL unicast subframes (non- ABS).
`d` and `u`	represent DL and UL unicast subframes (ABS).
`1,2,3,…`	represent MBSFN Data (MTCH) subframes. The number is the MBSFN Area ID.
$\underline{1}$, $\underline{2}$, $\underline{3}$, …	represent MBSFN Ctrl (MCCH) subframes. The number is the MBSFN Area ID.

2.11.2 Subframe Sequences

The ABS patterns and MBSFN areas assigned to a cell define a time-sequence of subframes for that cell.

Example: A cell uses TDD Configuration 2 and supports a single MBSFN Area with an ID of 1. We take a simple case when the subframe sequence repeats every 32 frames (i.e. SFN32 has the same subframe sequence as SFN0). The MCCH for the MBSFN area occurs in just one subframe. The cell is using ABS in the DL, but only in odd system frame numbers (SFN1, SFN3, …). So the subframe sequence could look something like this:

```
---SFN0--- ---SFN1--- ---SFN2--- ---SFN3--- ...
DSUD1DSU1D DSUD1dSU1d DSUD1DSU1D DSUD1dSU1d ...
```

2.11.3 Choice of Victim Subframe Type

When we calculate the SINR for a channel we need to account for the fact that the channel may only occur in particular subframes. The SINR that we calculate represents an average over those subframes, and so our choice of victim subframe type depends on the quantity we wish to calculate.

Example 1: To calculate MBSFN RS SINR for MBSFN Area ID 1, we would take the victim subframes to be those marked $\underline{1}$ or 1 since the MBSFN RS channel occurs in both those subframe types.

Example 2: To calculate MBSFN Data SINR for MBSFN Area 1, we would take the victim subframes to be those marked 1.

Example 3: To calculate MBSFN Ctrl SINR for MBSFN Area 1, we would take the victim subframes to be those marked $\underline{1}$.

Example 4: To calculate Unicast DL RS SINR for a cell, we would take the victim subframes to be those marked D or d in the subframe sequence of that cell.

Example 5: To calculate Unicast DL Data SINR for a cell, we would take the victim subframes to be those marked D in the subframe sequence of that cell, as the DL Data channel is blanked out in the d subframes.

To calculate a time-overlap factor, we need to compare the subframe sequences of the aggressor cells and the victim cell. We will demonstrate this with the following example.

2.11.4 Example Time-Overlap Calculation

Consider the calculation of Unicast DL Traffic SINR for a victim cell. We will consider the case when we have single interfering aggressor cell with a different subframe sequence to the victim. For simplicity we will assume that the subframe sequences on both cells repeat after 32 frames. (In general, if the two sequences repeat after different numbers of subframes, then we must consider a sequence length that is the lowest common multiple of the two.)

Aggressor:	DSUD$\underline{1}$DSU1D DSUD1dSU1d DSUD1DSU1D DSUD1dSU1d ...
Victim:	DSUDDDDDdd DSUDDDDDDD DSUdddDDDD DSUDDDDDDD ...

The victim subframes for the Unicast DL Traffic SINR calculation are the ones marked in **green**. Note that we ignore the victim ABS subframes (marked d) since they do not contain the channel of interest. The corresponding interfering subframes in the aggressor cell are marked in **red**, and we see that we have a mixture of interfering subframe types.

When summed over the full 32 frame sequence length, we find that there are a total of 216 victim subframes, and by counting the corresponding numbers of interfering subframes we get the following set of time-overlap factors:

$O^{time}_{\underline{1}\to D}$ = 1/216, $O^{time}_{1\to D}$ = 47/216, $O^{time}_{D\to D}$ = 72/216, $O^{time}_{d\to D}$ = 32/216,

$O^{time}_{S\to D}$ = 32/216, $O^{time}_{U\to D}$ = 32/216, $O^{time}_{u\to D}$ = 0.

Note that only the four factors on the top row are of use to us since we do not model interference from special subframes, nor do we explicitly model interference from one terminal's UL to another terminal's DL.

2.12 Calculation of Element-Overlap Factors

The element-overlap factor $O^{element}_{a\in A\rightarrow v\in V}$ gives the average number of aggressor REs of type a (in aggressor subframe type A) per victim RE of type v (in victim subframe type V). This factor allows us to model interference between different DL physical channels. The calculation of this factor is best described graphically.

2.12.1 Resource Element Types

We need to consider interference between the following RE types in aggressor and victim subframes. Note that the BCH channel from a cell will only receive interference from the BCH channels of other cells, and likewise for the SCH channel. Therefore we do not need to calculate element-overlap factors involving the BCH or SCH channels.

Each of the small boxes below represents an RE including cyclic prefix (CP). The REs have been drawn to scale in both the time direction (horizontal) and frequency direction (vertical).

(,) = (Unicast RS, Unicast Data/Ctrl). Δf = 15 kHz. Normal CP.

(,) = (Unicast RS, Unicast Data/Ctrl). Δf = 15 kHz. Extended CP.

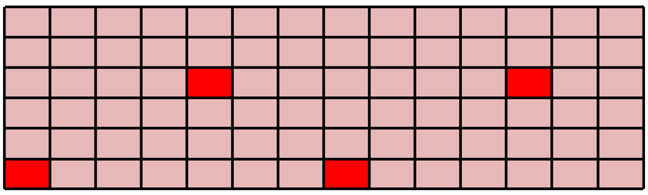
(,) = (MBSFN RS, MBSFN Data/Ctrl). Δf = 15 kHz. Extended CP.

(,) = (MBSFN RS, MBSFN Data/Ctrl). Δf = 7.5 kHz. Extended CP.

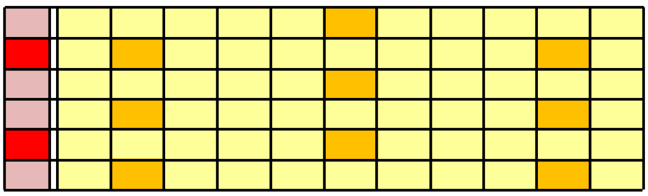
2.12.2 Resource Element Patterns in Subframes

The following pictures (each 1 ms wide and 90 kHz tall) provide examples of RE patterns for different types of subframe configuration. One should note that the REs in these pictures can have different areas because they are drawn with the CP. Think of each one of these REs as a box of energy. We must draw the boxes with the CP in order to correctly populate each picture with energy.

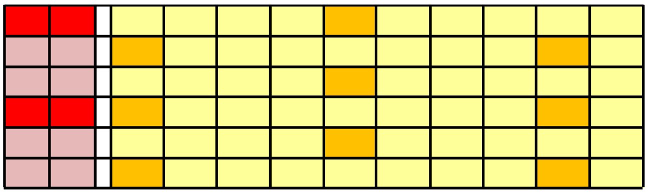
Example 1: DL Unicast subframe: TX = 1, PCI modulo 6 = 0.



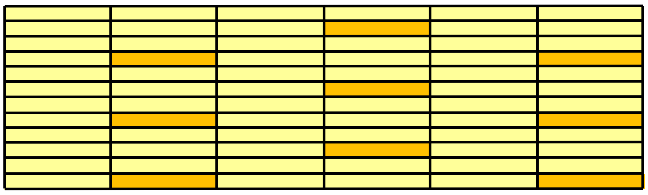
Example 2: MBSFN subframe: TX = 2, PCI modulo 3 = 1, Non-MBSFN Length = 1.



Example 3: MBSFN subframe: TX = 4, PCI modulo 3 = 2, Non-MBSFN Length = 2.



Example 4: MBSFN subframe: 7.5 kHz subcarriers, Extended CP, Non-MBSFN Length = 0.

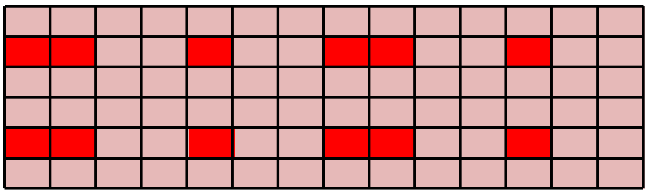


One should note that if we removed the CP from the REs then every RE would have the same area. This is an important point. Since our DL SINR calculations are expressed in terms of energies for REs *without* the CP, it means that our element-overlap factors can be found simply by drawing the RE patterns of the aggressor and victim subframes as in the previous pictures (i.e. *with* the CP) and then taking a *ratio of areas*. We will demonstrate this with the following example.

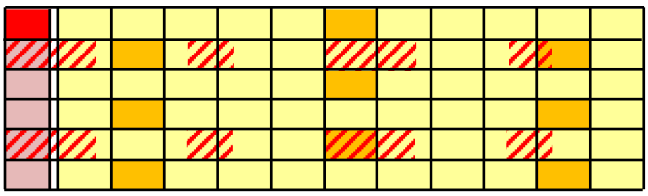
2.12.3 Example Element-Overlap Calculation

Consider the situation when we wish to calculate the MBSFN RS SINR and we have a DL Unicast aggressor subframe using normal CP.

Aggressor: DL Unicast subframe, TX = 4, PCI modulo 3 = 2



Victim: MBSFN subframe, TX = 1, PCI modulo 6 = 5, Non-MBSFN Length = 1.



The victim REs in this case are the nine orange boxes in the second picture. The red hatched lines show the portion of the victim subframe affected by the unicast RS elements of the aggressor subframe. A calculation shows that 1/7 of the orange area has hatched lines. Therefore in this example we get the following element-overlap factors:

$$O^{element}_{Unicast\ RS \to MBSFN\ RS} = 1/7$$

$$O^{element}_{Unicast\ Data/Ctrl \to MBSFN\ RS} = 6/7$$

This procedure of constructing RE patterns for the victim and interferer subframes and then examining how those patterns overlap is precisely how the simulator calculates element-overlap factors, and the method can be used for all RE types and subframes types. In situations where a cell has an unknown PCI, an average element-overlap factor is calculated by performing the overlap calculation described above for all possible PCI values, and then taking an averaging of the resulting factors.

2.12.4 Element-Overlap Calculation for RSSI calculations

The RE patterns also affect the calculation of Unicast RSSI and Multicast RSSI. The RSSI formula (50) is the same for both cases but differs in the choice of symbols and subframes used to perform the calculation.

For the unicast RSSI calculation: We restrict the victim subframe types V to DL unicast subframes (both ABS and non-ABS) and we are only concerned with the symbols containing unicast RS elements.

For the multicast RSSI calculation (for an MBSFN area): We restrict the victim subframe types V to subframes used by the MBSFN area (both Ctrl and Data subframes) and we are only concerned with the symbols containing multicast RS elements.

$$(RSSI)^{V}_{J,p,k} = N^{DL}_{p,k} + \sum_{q}\sum_{C \neq J}\sum_{A \in C}\sum_{a \in A} O^{freq}_{pq}\ O^{time}_{A \in C \to V \in J}\ \frac{n^{RE\ per\ SC}_{a \in A \to V}\left(n^{RB}_{q}\ n^{DL\ SC/RB}_{q}\right)\varepsilon^{a \in A}_{C,q}\ U^{a \in A}_{C} G^{DL\ Interf}_{C,k}}{L^{DL}_{Ck} \cdot T^{useful\ symbol}_{q}} \quad \textbf{(50)}$$

$N^{DL}_{p,k}$ is the DL thermal noise power over the whole carrier bandwidth as given by (133).

The frequency-overlap factor O^{freq}_{pq} maps power from the aggressor carrier bandwidth to the victim carrier bandwidth.

The time-overlap factor $O^{time}_{A \in C \to V \in J}$ accounts for any eICIC effects between cells J and C, as well as accounting for any other differences between the subframe sequences on the two cells.

$\varepsilon^{a \in A}_{C,q}$ is the EPRE of aggressor element type a on the aggressor cell C.

The factor $U^{a \in A}_{C}$ is a *generalised DL load factor* that accounts for both RE type and subframe type. For example, DL reference signal REs are not load dependent and so the generalised load factor for them is always 1 in all subframe types. As another example, Unicast Data/Ctrl REs are not used in ABS subframes, so the generalised load factor for them in those subframes is zero, while in non-ABS subframes the generalised load factor for them takes a value from 0 to 1 (equal to the DL cell load).

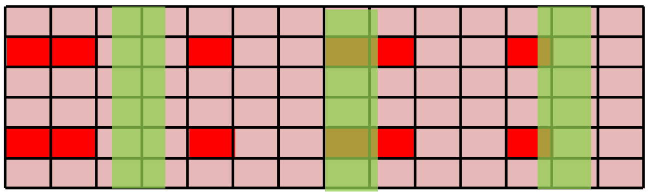
The factor $G^{DL\ interf}_{C,k}$ accounts for the beamforming interference gain when some of the load $U^{a \in A}_{C}$ is due to aggressor terminals using DL beamforming. See section on beamforming for details.

$\left(n^{RB}_{q}\ n^{DL\ SC/RB}_{q}\right)$ is the number of subcarriers on the aggressor carrier q.

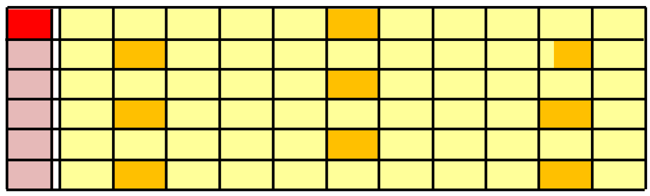
$n_{a\in A\rightarrow V}^{RE\ per\ SC}$ is the mean number of REs of type a per subcarrier (for a victim RSSI symbol). This can be thought of as a weight factor (between 0 and 1) giving the relative proportions of aggressor RE types. We now provide an example of its calculation.

Example: Consider the calculation of MBSFN RSSI for the victim subframe pattern shown in the second of the following pictures. The victim symbols over which the MBSFN RSSI is calculated are the three columns containing orange boxes. The corresponding portions of an aggressor unicast subframe are shown in the picture above it with a green overlay.

Aggressor: DL Unicast subframe, TX = 4, PCI modulo 3 = 2



Victim: MBSFN subframe, TX = 1, PCI modulo 6 = 5, Non-MBSFN Length = 1.



A calculation shows that 1/7 of the green area has red (i.e. unicast RS energy) underneath it. So we get the result

$$n_{Unicast\ RS\rightarrow V}^{RE\ per\ SC} = \frac{1}{7}$$

$$n_{Unicast\ Data/Ctrl\rightarrow V}^{RE\ per\ SC} = \frac{6}{7}$$

2.13 DL RECEIVED INTERFERENCE EPRE

All DL SINR calculations are expressed in terms of the received signal EPRE and interference EPRE for an appropriate RE type and subframe type. For a victim RE of type v in subframe type V, the total received interfering EPRE from other cells C is given by

$$I_{J,p,k}^{v\in V} = \sum_{q}\sum_{C\neq J}\sum_{A\in C}\sum_{a\in A}\left(O_{pq}^{freq}\ W_q\ /\ W_p\right)\ O_{A\in C\rightarrow V\in J}^{time}\ O_{a\in A\rightarrow v\in V}^{element}\ \frac{\varepsilon_{C,q}^{a\in A}\ U_C^{a\in A}\ G_{C,k}^{DL\ Interf}\ \Theta_{JC}^{v,a}}{L_{Ck}^{DL}} \qquad \textbf{(51)}$$

The above formula fully describes how aggressor cells produce an interfering DL EPRE for a victim resource element.

The summation over 'A' indicates a sum over all subframe types on aggressor cell C, and the summation over 'a' indicates a sum over all RE types in aggressor subframe A.

The frequency-overlap factor $\left(O_{pq}^{freq}\, W_q \,/\, W_p\right)$ maps EPRE from the aggressor carrier q to the victim carrier p.

The time-overlap factor $O_{A\in C\rightarrow V\in J}^{time}$ accounts for any eICIC effects between cells J and C, as well as accounting for any other differences between subframe sequences on the two cells.

The element-overlap factor $O_{a\in A\rightarrow v\in V}^{element}$ accounts for interference between *all* DL channel types (e.g. between DL RS and DL Data/Ctrl, as well as between unicast and multicast channels).

The factor $U_C^{a\in A}$ is a *generalised DL load factor* that accounts for both RE type and subframe type. For example, DL reference signal REs are not load dependent and so the generalised load factor for them is always 1 in all subframe types. As another example, Unicast Data/Ctrl REs are not used in ABS subframes, so the generalised load factor for them in those subframes is zero, while in non-ABS subframes the generalised load factor for them takes a value from 0 to 1 (equal to the DL cell load).

The factor $G_{C,k}^{DL\,Interf}$ accounts for the beamforming interference gain when some of the load $U_C^{a\in A}$ is due to aggressor terminals using DL beamforming. See section on beamforming for details.

The factor $\Theta_{JC}^{v,a}$ is the (frequency-based) *ICIC factor* and is only applicable when cells J and C are both using the same carrier and ICIC scheme, and the resource element types v and a are both *Unicast Data* or *Unicast Ctrl*. In that case $\Theta_{JC}^{v,a}$ takes the value Θ_{JC}^{ICIC} as defined in Chapter 6. In all other cases $\Theta_{JC}^{v,a}$ has the value 1.

2.14 MBSFN Calculations

2.14.1 MBSFN SINR Calculations without Multipath Modelling

When calculating MBSFN quantities, we must account for the fact that cells that have the same carrier, MBSFN Area ID, and MBSFN Sync ID can provide increased signal and reduced interference provided that the signals are received within a sufficiently small time period. *Note: The weight functions below only apply to cells serving a particular MBSFN Area ID. Interference from different MBSFN Areas or from non-MBSFN subframes is handled separately using* (57).

To calculate the received signal and interference for an MBSFN area, we must first determine the *reference cell* for the MBSFN area. We define this as being the closest cell that supports that MBSFN area while still providing adequate unicast coverage (i.e. RSRP, RSRQ, BCH/SCH SINR all ok). We then calculate the relative delay T_{JCk} for every other cell C in the MBSFN area with respect to the reference cell J.

$$T_{JCk} = \frac{\left(d_{Ck} - d_{Jk}\right)}{c} \qquad \textbf{(52)}$$

where

d_{Jk} is the distance from (the dominant antenna of) cell J to terminal k,
d_{Ck} is the distance from (the dominant antenna of) cell C to terminal k,
c is the speed of light.

In the ideal situation where the link from cell C has no multipath components, we have the following weight function for cell C that gives the proportion of useful signal energy.

$$w_{JCk} = \begin{cases} \left(1 + \frac{T_{JCk}}{T^{useful\ symbol}}\right) & \text{if } -T^{useful\ symbol} \leq T_{JCk} < 0 \\ 1 & \text{if } 0 \leq T_{JCk} < T^{CP} \\ \left(1 - \frac{T_{JCk} - T^{CP}}{T^{useful\ symbol}}\right) & \text{if } T^{CP} \leq T_{JCk} < T^{CP} + T^{useful\ symbol} \\ 0 & \text{otherwise} \end{cases} \quad (53)$$

where

T^{CP} is the duration of the cyclic prefix of an MBSFN symbol.

$T^{useful\ symbol}$ is the duration of an MBSFN symbol without CP.

MBSFN RSRP

$$(RSRP)_{J,p,k}^{v \in V} = \left(\frac{1}{T_p^{useful\ symbol}}\right) \sum_C \left(\frac{\varepsilon_{C,p}^v \cdot w_{JCk}}{L_{Ck}^{DL}}\right) \quad (54)$$

MBSFN RSRQ

$$(RSRQ)_{J,p,k}^{v \in V} = \frac{n_p^{RB} (RSRP)_{J,p,k}^{v \in V}}{(RSSI)_{J,p,k}^{V}} \quad (55)$$

where the MBSFN RSRP and MBSFN RSSI are calculated using (54) and (50) respectively .

MBSFN RS SINR, MBSFN Data SINR, MBSFN Ctrl SINR

To calculate MBSFN SINR for RS, Data, or Ctrl channels we use the following formula that expresses SINR in terms of EPREs. For an MBSFN RE of type v in subframe type V the SINR has the following form with $\sum_C$ representing a summation over all cells in the MBSFN area.

$$(SINR)_{J,p,k}^{v \in V} = \frac{\sum_C \left(\frac{\varepsilon_{C,p}^v \cdot w_{JCk}}{L_{Ck}^{DL}}\right)}{\varepsilon_v^{thermal} + N_{J,p,k}^{v \in V} + \sum_C \left(\frac{\varepsilon_{C,p}^v \cdot (1 - w_{JCk})}{L_{Ck}^{DL}}\right)} \quad (56)$$

where

$\varepsilon_v^{thermal}$ is the thermal EPRE for the RE type of interest (RS/Data/Ctrl).
$\varepsilon_{C,q}^v$ is the TX EPRE for the RE type of interest (RS/Data/Ctrl).
$N_{J,p,k}^{v \in V}$ is the total interfering EPRE from other subframe types (i.e. from DL unicast subframes or subframes of other MBSFN areas).

Note that the formula for $N_{J,p,k}^{v \in V}$ below is almost the same as (51) but the summation over aggressor subframe types A is restricted to $A \neq V$, and there is no (frequency-based) *ICIC factor*.

$$N_{J,p,k}^{v \in V} = \sum_q \sum_{C \neq J} \sum_{A \in C, A \neq V} \sum_{a \in A} \left(O_{pq}^{freq}\, W_q \,/\, W_p\right) O_{A \in C \to V \in J}^{time}\, O_{a \in A \to v \in V}^{element}\, \frac{\varepsilon_{C,q}^{a \in A}\, U_C^{a \in A} G_{C,k}^{DL\ Interf}}{L_{Ck}^{DL}} \quad (57)$$

2.14.2 MBSFN SINR Calculations with Multipath Modelling

When the link to cell C has multipath components (described by the multipath model on cell C) then the interfering power is divided amongst the multipath components according to the tap strengths of the multipath model. Each multipath component then provides a contribution to the SINR in the manner described in the previous section, but with the relative delay for a component modified by its tap delay value as follows:

$$T_{JCk} = \frac{(d_{Ck} - d_{Jk})}{c} + T^{tap\ delay} \quad (58)$$

2.14.3 Calculations of Coverage Probabilities for MSBFN

The expressions for MBSFN RSRP, MBSFN RSRQ and MBSFN SINR given by (54), (55) and (56) refer to values in the absence of log-normal fading. In general there are several contributions to the total signal power and each contribution will be subject to log-normal fading. The standard method of calculating signal coverage probability (when there is only a single signal component) is not suitable for calculating the coverage probability for MBSFN quantities. A correct calculation must account for fading in all the component signals and for the fact that these fades will be partially correlated. We allow the user to specify two correlation factors in our tool. The inter-site correlation coefficient (c^{inter}) describes the degree of correlation between fades to cells on different sites, and the intra-site correlation coefficient (c^{intra}) describes the degree of correlation between fade to cells on the same site. In the real world c^{inter} is typically 0.5 and c^{intra} will be larger (the default in Asset is 0.8).

To calculate coverage probabilities for MBSFN we use a generalisation of the technique described by Mehta et al [1] for approximating a sum of log-normal random variables. Our method is able to account for correlated log-normal fading with the two correlation coefficients c^{inter} and c^{intra}. As well as being able to calculate the distribution of total MBSFN signal power (which is well–approximated by a log-normal distribution) we are also able to calculate the distribution of MBSFN RSRQ and MBSFN SINR which in general are not well approximated by log-normal distributions. We have compared the results produced by our method against theoretically correct values obtained from a Monte Carlo approach, and have found that our method provides an excellent approximation for shadow fading standard deviations from 0 dB to 20 dB.

Example 1: Consider the following set of 18 MBFSN signal powers at a location, which have been ordered by cell name to better highlight cells on the same site. All signals in this example are received within the CP and so the weighting term w_{JCk} is 1 for all of them. The total MBSFN RSRP in the absence of fading is just the sum of these powers and equals -100.32 dBm. In other words, this is the MBSFN RSRP for a shadow fading standard deviation of 0 dB.

Cell	**Multicast RSRP (dBm)**
Node_112A	-140
Node_113A	-110
Node_113B	-120
Node_114A	-110
Node_114B	-134
Node_114C	-118
Node_122B	-134
Node_123B	-127
Node_152B	-131
Node_106B	-132
Node_107A	-138

Node_107B	-112
Node_108A	-136
Node_108B	-105
Node_108C	-126
Node_109A	-137
Node_109B	-136
Node_109C	-105
Total Power	**-100.32 dBm**

The following figure shows how coverage probability varies with MBSFN RSRP requirement for the case when the shadow fading standard deviation is 8 dB and all fades are *perfectly correlated*. The horizontal axis is the MBSFN RSRP requirement with respect to the total signal power in the absence of fading. In other words, zero on the horizontal axis corresponds to an MBSFN RSRP requirement of -100.32 dBm. Since all the fades are perfectly correlated, we could get the exact same graph by assuming we have a single cell providing all of the signal power of -100.32 dBm. So this is a trivial case. It is just included here for comparison against the more complicated cases that follow.

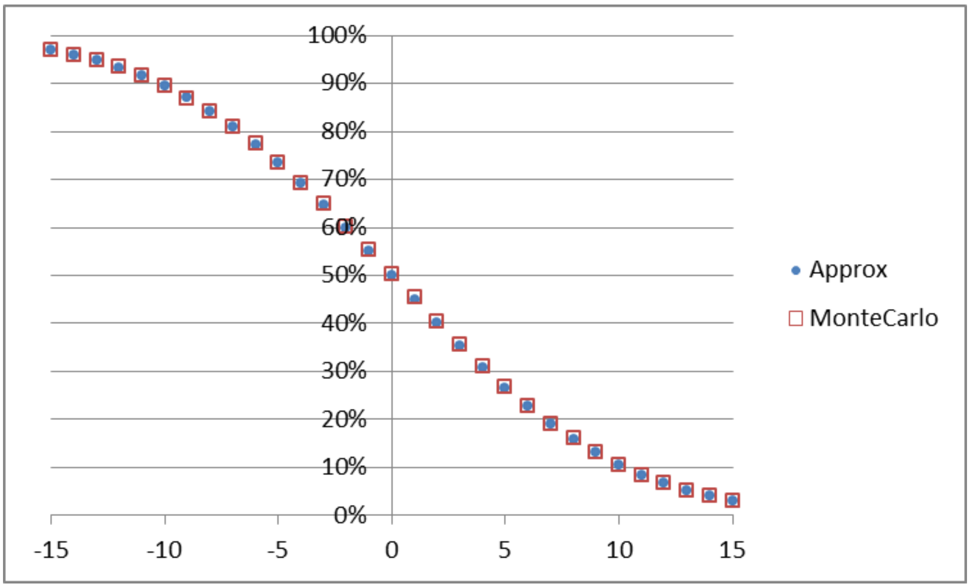


Figure 6: MBSFN RSRP Coverage Probability vs MBSFN RSRP Requirement (perfectly correlated fades).

The next figure shows how things change when fades are *partially correlated* with correlation factors of c^{inter} = 0.5 and c^{intra} = 0.8. As before, zero on the horizontal axis corresponds to a signal threshold of -100.32 dBm. Compared to the previous graph, the curve has moved to the right and has become slightly compressed in the horizontal direction.

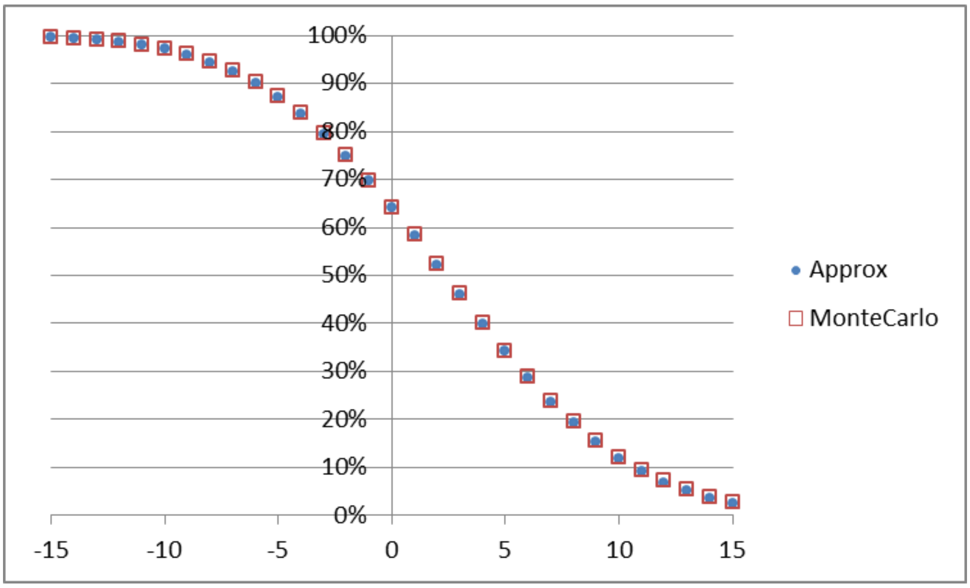


Figure 7: MBSFN RSRP Coverage Probability vs MBSFN RSRP Requirement (partially correlated fades).

The following figure shows both curves together and demonstrates how partially correlated fading affects fade margin. At a 50% coverage probability level, the case with perfectly correlated fading gives a fade margin of 0 dB which is the exact same result we would expect for a unicast signal. The curve with partially correlated fades gives a fade margin of minus 2.34 dB which means that partially correlated fading has actually improved coverage probability. The 2.34 dB figure is also telling us that the MBSFN RSRP value of -100.32 dBm (which assumes no log-normal fading) is actually 2.34 dB lower than the average MBSFN RSRP when there is (partially correlated) fading. At a 90% coverage probability level, the reduction in fade margin is even larger (about 4 dB) compared to the case when fades are perfectly correlated.

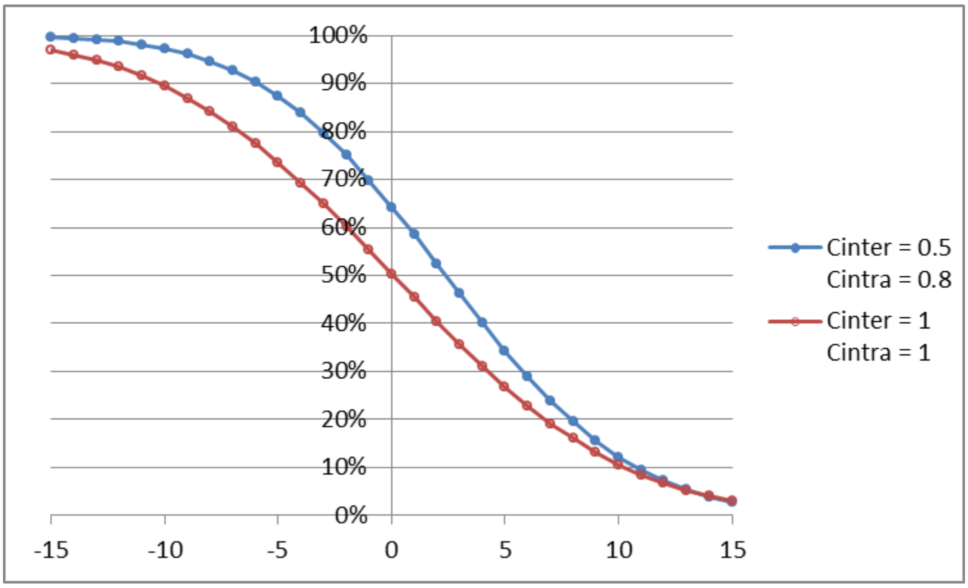


Figure 8: Comparison of previous two figures.

Example 2: We now show how our method performs when calculating the coverage probability for MBSFN Data SINR. The following table gives a set of received MBSFN Data EPRE values for a set of 18 cells. Note that cells can contribute to both signal and interference. Each listed signal energy has been scaled by its weight factor (w_{JCk}) and each interfering energy (apart from thermal noise) has been scaled by its weight factor $(1 - w_{JCk})$.

Cell	**Signal (dBm/Hz)**	**Interference (dBm/Hz)**
Node_6A	-163.55	
Node_8B	-170.56	-200.04
Node_8C	-168.56	-198.04
Node_9C	-164.55	
Node_11C	-168.55	
Node_36B	-170.55	
Node_37B	-160.55	
Node_38B	-165.62	-183.48
Node_39B	-164.76	-177.85
Node_41B	-171.90	-182.68
Node_41C	-161.90	-172.68
Node_42C	-165.69	-180.56
Node_43C	-162.55	
Node_45C	-170.55	
Node_54C	-165.76	-178.86
Node_55C	-168.67	-184.24
Node_128C	-168.55	
Node_132C	-170.55	
Thermal Noise		-173.93
Total	**-153.02**	**-168.34**

The SINR without fading is given by -153.02 – 168.34 = 15.32 dB. The following figure shows how the corresponding SINR coverage probability varies with SINR requirement. The curve has been calculated for a shadow fading standard deviation of 13 dB and correlation coefficients c^{inter} = 0.5 and c^{intra} = 0.8. The horizontal axis is marked in terms of relative SINR requirement (in dB). In other words, zero on the horizontal axis corresponds to an SINR requirement of 15.32 dB.

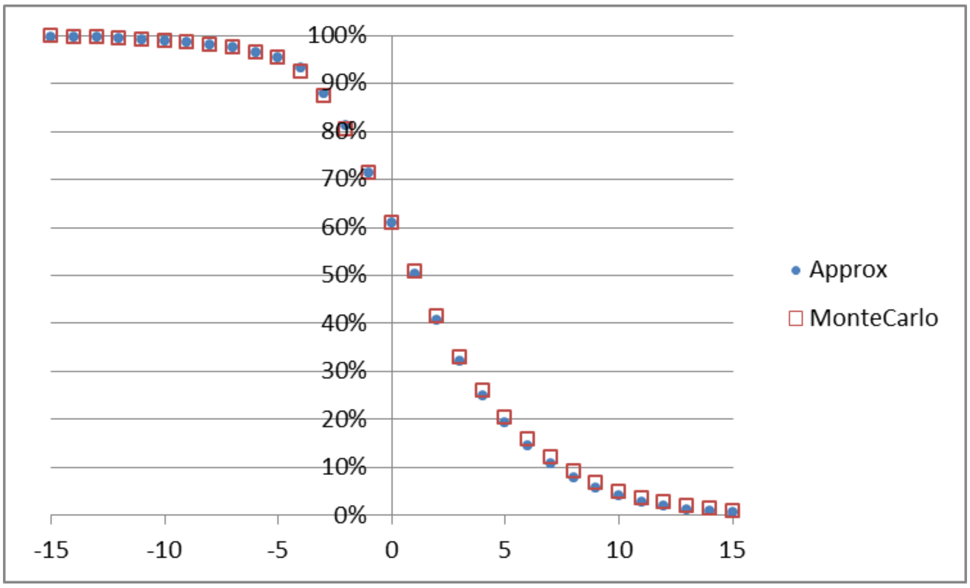


Figure 9: MBSFN Data SINR Coverage Probability vs SINR Requirement. (13 dB shadow fading std. deviation).

Notice that unlike the previous curves that dealt with signal strength, we no longer have a symmetrical curve about the 50% point. This demonstrates that even though the individual fades follow log-normal distributions, the resulting distribution of SINR is not log-normal. This is especially true for large shadow fading standard deviations and for situations when there are correlations between signal and interference terms. Our method provides a good approximation to the correct result, even though the resulting SINR distribution is not log-normal.

If we recalculate the above graph for a larger shadow-fading standard deviation of 20dB our method becomes less accurate (see following figure) but it still gives a good result for probabilities larger than 90% and these are the probabilities of most interest for planning a real network.

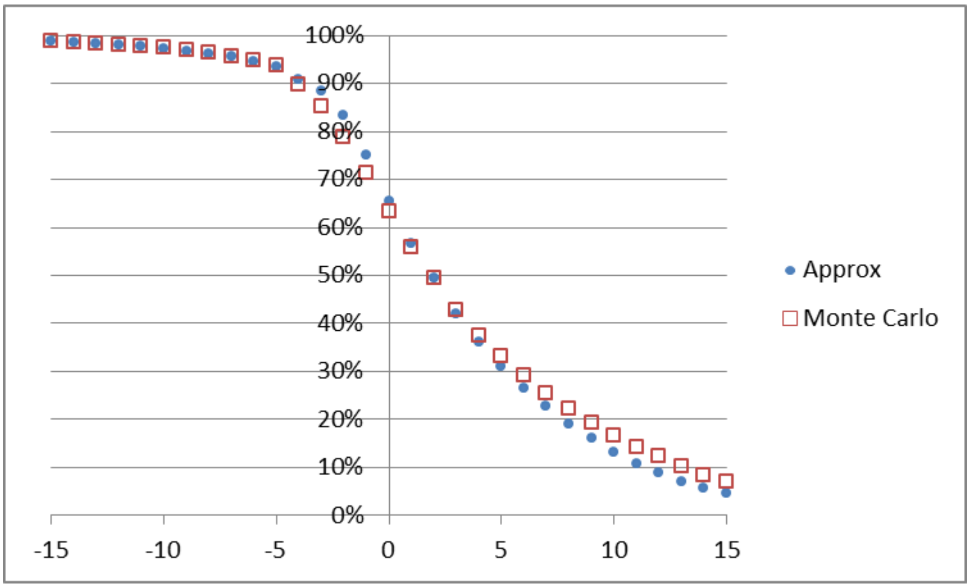
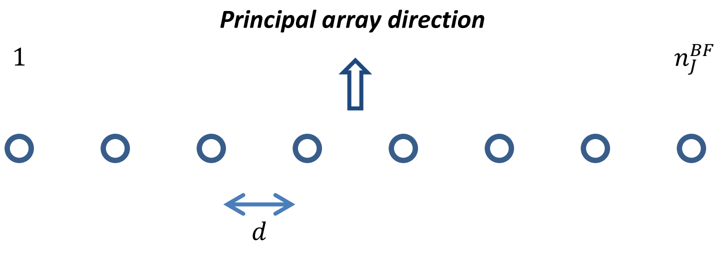


Figure 10: MBSFN Data SINR Coverage Probability vs SINR Requirement. (20 dB shadow fading std. deviation).

[1] Neelesh Mehta, Jingxian Wu, Andreas Molisch, Jin Zhang. "*Approximating a Sum of Random Variables with a Lognormal*". IEEE Transactions on Wireless Communications, 2007.

2.15 Beamforming Antenna Systems

We model a beamforming antenna on a cell J as a linear array of n_J^{BF} identical elements separated by distance d. Each element has the same antenna mask pattern. The principal array direction corresponds to the effective antenna azimuth (i.e. the physical azimuth plus any offset in the horizontal mask). The gain due to beamforming can be calculated independently of the antenna mask, so in all of the following formulas we can consider the array elements to be isotropic radiators without loss of generality.



2.15.1 Steering Vector for a Terminal

For a cell J and terminal k with azimuth $\theta_{J,k}$ with respect to the principal array direction we define the steering vector $\overrightarrow{S_{J,k}}$ as

$$\overrightarrow{S_{J,k}} = \left(1\,,\ e^{\alpha_{J,k}},\ e^{2\alpha_{J,k}}\,, \ldots,\ e^{(n_J^{BF}-1)\alpha_{J,k}}\right)^T \quad (59)$$

where

$$\alpha_{J,k} = j\,(2\pi d/\lambda)\sin(\theta_{J,k}) \quad (60)$$

and λ is the operating wavelength. We always take the element spacing d to be $\lambda/2$ so we have

$$\alpha_{J,k} = j\,\pi\sin(\theta_{J,k}). \quad (61)$$

The components of the steering vector $\overrightarrow{S_{J,k}}$ describe how the set of n_J^{BF} path-lengths between the terminal and the array elements affect the relative phases of the received signal at the elements.

2.15.2 Matrix Structure

Most matrices in the beamforming equations are weighted sums of matrices of the form $\overrightarrow{S_{J,k}}\,\overrightarrow{S_{J,k}}^H$ where the superscript H signifies the Hermitian adjoint operator (i.e. conjugate transpose). The matrix $\overrightarrow{S_{J,k}}\,\overrightarrow{S_{J,k}}^H$ is Hermitian, positive-definite, and has a band-diagonal structure. For example when $n_J^{BF} = 4$ we have the matrix

$$\overrightarrow{S_{J,k}}\,\overrightarrow{S_{J,k}}^H = \begin{pmatrix} 1 & e^{-\alpha_{J,k}} & e^{-2\alpha_{J,k}} & e^{-3\alpha_{J,k}} \\ e^{\alpha_{J,k}} & 1 & e^{-\alpha_{J,k}} & e^{-2\alpha_{J,k}} \\ e^{2\alpha_{J,k}} & e^{\alpha_{J,k}} & 1 & e^{-\alpha_{J,k}} \\ e^{3\alpha_{J,k}} & e^{2\alpha_{J,k}} & e^{\alpha_{J,k}} & 1 \end{pmatrix}. \quad (62)$$

Note that the first column of this matrix matches the vector $\overrightarrow{S_{J,k}}$. This simple matrix structure makes it possible to store weighted sums of these matrices as weighted sums of steering vectors instead.

2.15.3 Adaptive Beamforming: The Downlink

For the DL we begin by considering (optimal) adaptive beamforming with the transmitted traffic power $P_{J,k}$ for served terminal k shared equally between the n_J^{BF} array elements. In order to steer power towards terminal k, the complex weights $\overrightarrow{w_{J,k}}^*$ applied to the transmitted signals are chosen to compensate for the phase differences described by the steering vector $\overrightarrow{S_{J,k}}$, allowing the signals to combine constructively at the terminal.

$$\overrightarrow{w_{J,k}}^* = \sqrt{P_{J,k}/n_J^{BF}}\ \overrightarrow{S_{J,k}}^* . \tag{63}$$

In (63) the relative phases of the signals applied to the array elements are given by $\overrightarrow{S_{J,k}}^*$ and the transmitted signal amplitude of $\sqrt{P_{J,k}/n_J^{BF}}$ gives each array element a transmit signal power of $P_{J,k}/n_J^{BF}$.

For any set of weights $\overrightarrow{w_{J,k}}^*$, the azimuthal distribution of radiated power will have peaks and troughs due to the signals from the array elements combining constructively and destructively. The effective power radiated in an arbitrary direction with steering vector $\vec{S}$ is given by

$$\left| \overrightarrow{w_{J,k}}^H \vec{S} \right|^2 \tag{64}$$

which can be expanded and written as

$$\vec{S}^H \boldsymbol{R}_{\boldsymbol{J,k}}^{\boldsymbol{DL}} \vec{S} \tag{65}$$

where

$$\boldsymbol{R}_{\boldsymbol{J,k}}^{\boldsymbol{DL}} = \overrightarrow{w_{J,k}}\, \overrightarrow{w_{J,k}}^H . \tag{66}$$

We call $\boldsymbol{R}_{\boldsymbol{J,k}}^{\boldsymbol{DL}}$ the *DL TX power matrix for terminal k on cell J* and it describes the azimuthal power distribution (i.e. beamforming pattern) for the beam that serves the terminal. For the choice of weights in (63), the DL power matrix for the terminal is given by

$$\boldsymbol{R}_{\boldsymbol{J,k}}^{\boldsymbol{DL}} = \left(P_{J,k}/n_J^{BF}\right) \overrightarrow{S_{J,k}}\, \overrightarrow{S_{J,k}}^H . \tag{67}$$

2.15.4 Adaptive Beamforming: DL Signal Power Gain (and DL SINR Gain)

With adaptive DL beamforming, the effective signal power radiated towards a served terminal k is found by substituting (67) into (65) to give

$$\overrightarrow{S_{J,k}}^H \boldsymbol{R}_{\boldsymbol{J,k}}^{\boldsymbol{DL}} \overrightarrow{S_{J,k}} = \left(P_{J,k}/n_J^{BF}\right) \left(\overrightarrow{S_{J,k}}^H \overrightarrow{S_{J,k}} \right)^2 = n_J^{BF}\ P_{J,k}. \tag{68}$$

So compared to the non-beamforming case (where the power $P_{J,k}$ would be allocated to a single antenna element instead of being shared across all elements) the DL signal power gain (and therefore DL SINR gain) is simply n_J^{BF}.

$$G_{J,k}^{DL\ SINR} = G_{J,k}^{DL\ Signal} = \left(\overrightarrow{S_{J,k}}^H \boldsymbol{R}_{\boldsymbol{J,k}}^{\boldsymbol{DL}} \overrightarrow{S_{J,k}} \right) / P_{J,k} = n_J^{BF} . \tag{69}$$

2.15.5 Adaptive Beamforming: DL Interference Power Gain

To calculate how DL beamforming on a cell J affects the DL interference caused to other cells, we must consider all of its served terminals k that use DL beamforming. By summing the DL TX power matrices of these terminals we obtain the *total DL TX power matrix* ($\boldsymbol{R}_J^{DL}$) describing the overall azimuthal power distribution due to DL beamforming connections on the cell.

$$\boldsymbol{R}_J^{DL} = \sum_{k \in J} \boldsymbol{R}_{J,k}^{DL}. \tag{70}$$

By analogy with (65), the effective interfering TX power radiated towards a victim terminal v is found by operating on $\boldsymbol{R}_J^{DL}$ with the steering vector of the victim terminal ($\overrightarrow{S_{J,v}}$) as follows

$$\overrightarrow{S_{J,v}}^H \boldsymbol{R}_J^{DL} \overrightarrow{S_{J,v}}. \tag{71}$$

Note that in the non-beamforming case with a single antenna element, the effective interfering TX power from the DL beamforming terminals would be given by

$$\sum_{k \in J} P_{J,k}. \tag{72}$$

Also note that the trace of the matrix $\boldsymbol{R}_J^{DL}$ has the value

$$Tr\left(\boldsymbol{R}_J^{DL}\right) = \sum_{k \in J} P_{J,k}. \tag{73}$$

Therefore compared to the non-beamforming case with a single antenna element, the DL interference from the beamformed terminals on cell J to a victim terminal v gets a beamforming gain given by the ratio of (71) and (72) which gives

$$G_{J,v}^{DL\ BF} = \overrightarrow{S_{J,v}}^H \frac{\boldsymbol{R}_J^{DL}}{Tr\left(\boldsymbol{R}_J^{DL}\right)} \overrightarrow{S_{J,v}}. \tag{74}$$

Note that the scalar quantity $Tr\left(\boldsymbol{R}_J^{DL}\right)$ acts as a natural normalisation factor for the DL TX power matrix.

In general, not all terminals will be served by DL beamforming. Therefore when calculating interference from an aggressor cell J to a victim terminal v, we account use the following factor to scale the interference

$$G_{J,v}^{DL\ Interf} = \Lambda_J^{DL} G_{J,v}^{DL\ BF} + \left(1 - \Lambda_J^{DL}\right). \tag{75}$$

where $\Lambda_J^{DL\ BF}$ is the proportion of the DL load on cell J due to beamforming. So as the proportion of DL load due to beamforming increases from 0 to 1, the factor $G_{J,v}^{DL\ Interf}$ increases from 1 to $G_{J,v}^{DL\ BF}$.

2.15.6 Adaptive Beamforming: The Uplink

Although UL beamforming has not been formalised in the standards, we allow support for two methods of UL beamforming. For both methods, UL beamforming provides an UL SINR gain that varies with azimuth. We treat this UL SINR gain as a reduction in an UL bearer's SINR requirement.

UL SINR

For any terminal k that produces UL interference on the beamforming antenna of a cell J, we define the *UL RX power matrix* $\boldsymbol{R}_{J,k}^{UL}$ as

$$\boldsymbol{R}_{J,k}^{UL} = P_{J,k}\, \overrightarrow{S_{J,k}}\, \overrightarrow{S_{J,k}}^H \tag{76}$$

where $P_{J,k}$ is the UL received interfering power per element from terminal k, and $\overrightarrow{S_{J,k}}$ is the corresponding steering vector.

For any set of UL beamforming weights ($\vec{w}^*$) applied to the received signals on the elements, the resulting UL RX signal power from terminal k is found by operating on its power matrix ($\boldsymbol{R}_{J,k}^{UL}$) with the UL weights as follows

$$(\text{UL RX Signal Power})_{J,k} = \vec{w}^H \boldsymbol{R}_{J,k}^{UL}\, \vec{w}. \tag{77}$$

Therefore the UL SINR for a served terminal k using a set of beamforming weights $\overrightarrow{w_{J,k}}^*$ is given by

$$(\text{UL SINR})_{J,k} = \frac{\overrightarrow{w_{J,k}}^H \boldsymbol{R}_{J,k}^{UL}\, \overrightarrow{w_{J,k}}}{\overrightarrow{w_{J,k}}^H \boldsymbol{R}_{J}^{UL}\, \overrightarrow{w_{J,k}}} \tag{78}$$

where the numerator is the received signal power from terminal k and the denominator is the total received interference and noise power. The *total UL noise matrix* $\boldsymbol{R}_{J}^{UL}$ is defined as the sum of the UL RX power matrices of the interfering ("aggressor") terminals plus a thermal noise term

$$\boldsymbol{R}_{J}^{UL} = N_J\, \boldsymbol{I}_J + \sum_{a \notin J} \boldsymbol{R}_{J,a}^{UL} \tag{79}$$

where $\boldsymbol{I}_J$ is the $n_J^{BF} \times n_J^{BF}$ identity matrix, and N_J is the thermal noise power per element.

The UL SINR depends on the choice of beamforming weights. We support two methods of choosing these weights: "*Maximise UL Signal*" and "*Maximise UL SINR*".

2.15.7 Adaptive Beamforming: "Maximise UL Signal" Method

In this method the UL beamforming weights for a served terminal k are chosen to maximise the UL received signal power for the terminal. The weights are chosen to compensate for the phase differences between received signals at the array elements as follows

$$\overrightarrow{w_{J,k}}^* = \left(1\,, e^{-\alpha_{J,k}}\,, e^{-2\alpha_{J,k}}\,,\ \ldots,\ e^{-(n_J-1)\alpha_{J,k}}\right)^T = \overrightarrow{S_{J,k}}^*. \tag{80}$$

Apart from a scale factor, these are the same set of weights used for maximising signal when beamforming in the DL. Using the above weights the UL SINR in (78) reduces to

$$(\text{UL SINR})_{J,k} = \frac{\left(n_J^{BF}\right)^2 P_{J,k}}{\overrightarrow{S_{J,k}}^H \boldsymbol{R}_{J}^{UL} \overrightarrow{S_{J,k}}}. \tag{81}$$

The SINR for the non-beamforming case with a single antenna element is given by

$$\frac{P_{J,k}}{N_J + \sum_{a \notin J} P_{J,a}}. \qquad \textbf{(82)}$$

Also note that the trace of the matrix $\boldsymbol{R}_J^{UL}$ is simply related to the denominator of (82) as follows

$$Tr\left(\boldsymbol{R}_J^{UL}\right) = n_J^{BF}\left(N_J + \sum_{a \notin J} P_{J,a}\right). \qquad \textbf{(83)}$$

Therefore compared to the non-beamforming case, this method of UL beamforming increases the UL SINR for served terminal k by a factor of $G_{J,k}^{UL\ SINR}$ which is the SINR in (81) divided by that in (82).

$$G_{J,k}^{UL\ SINR} = \frac{n_J^{BF}}{\overrightarrow{S_{J,k}}^H \dfrac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)} \overrightarrow{S_{J,k}}}. \qquad \textbf{(84)}$$

Note that the scalar quantity $Tr\left(\boldsymbol{R}_J^{UL}\right)$ acts as a natural normalisation factor for the UL noise matrix.

2.15.8 Adaptive Beamforming: "Maximise UL SINR" Method

Note: There are several methods of optimal beamforming in the UL (i.e. MMSE, Minimum Output Energy, and Max SINR) and they can be shown to be equivalent to each other.

In this method, the beamforming weights for a served terminal k are chosen to maximise the UL SINR. Note that we only care about *relative* weights, since scaling all weights by a fixed factor of x scales both signal and interference powers by x^2 thus leaving the UL SINR unchanged.

We can maximise the UL SINR for a served terminal k by minimising the denominator in (78) subject to the constraint that the total received signal $\overrightarrow{w_{J,k}}^H \overrightarrow{S_{J,k}}$ has some fixed amplitude and phase of our choosing c. So we have the minimisation problem

$$\min_{\overrightarrow{w_{J,k}}} \left(\overrightarrow{w_{J,k}}^H \boldsymbol{R}_J^{UL} \overrightarrow{w_{J,k}}\right) \quad \text{subject to} \quad \overrightarrow{w_{J,k}}^H \overrightarrow{S_{J,k}} = c. \qquad \textbf{(85)}$$

This can be solved using the method of Lagrange multipliers by defining the Lagrangian

$$\mathcal{L}\left(\overrightarrow{w_{J,k}}, \lambda\right) = \left(\overrightarrow{w_{J,k}}^H \boldsymbol{R}_J^{UL} \overrightarrow{w_{J,k}}\right) - \lambda\left(\overrightarrow{w_{J,k}}^H \overrightarrow{S_{J,k}} - c\right) \qquad \textbf{(86)}$$

and differentiating with respect to $\overrightarrow{w_{J,k}}^H$, while noting that $\overrightarrow{w_{J,k}}^H$ and $\overrightarrow{w_{J,k}}$ can be treated as independent variables.

$$\frac{\partial \mathcal{L}}{\overrightarrow{w_{J,k}}^H} = 0 \quad \Rightarrow \quad \boldsymbol{R}_J^{UL}\overrightarrow{w_{J,k}} - \lambda \overrightarrow{S_{J,k}} = 0 \quad \Rightarrow \quad \overrightarrow{w_{J,k}} = \lambda\left(\boldsymbol{R}_J^{UL}\right)^{-1} \overrightarrow{S_{J,k}}. \qquad \textbf{(87)}$$

Substituting these weights into the SINR expression in (78) gives

$$\text{UL SINR} = \frac{|\lambda|^2}{|\lambda|^2} \cdot \frac{P_{J,k}\left(\overrightarrow{S_{J,k}}^H \left(\boldsymbol{R}_J^{UL}\right)^{-1} \overrightarrow{S_{J,k}}\right)^2}{\overrightarrow{S_{J,k}}^H \left(\boldsymbol{R}_J^{UL}\right)^{-1} \overrightarrow{S_{J,k}}} = P_{J,k}\, \overrightarrow{S_{J,k}}^H \left(\boldsymbol{R}_J^{UL}\right)^{-1} \overrightarrow{S_{J,k}}. \qquad \textbf{(88)}$$

As before we compare this to the non-beamforming UL SINR described by (82) and find that this method of UL beamforming increases the UL SINR for the served terminal k by a factor of

$$G_{J,k}^{UL\,SINR} = P_{J,k}\,\overrightarrow{S_{J,k}}^{H}\left(\boldsymbol{R}_J^{UL}\right)^{-1}\overrightarrow{S_{J,k}}\ /\ \left(\frac{P_{J,k}}{N_J + \sum_{a\notin J} P_{J,a}}\right) \tag{89}$$

Using (83) we can rewrite (89) as

$$G_{J,k}^{UL\,SINR} = \overrightarrow{S_{J,k}}^{H}\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)^{-1}\overrightarrow{S_{J,k}}\ /\ n_J^{BF}. \tag{90}$$

where $\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)^{-1}$ is the inverse of the *normalised* UL noise matrix $\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)$.

2.15.9 Averaging Beamforming Matrices over Snapshots

When producing plots in the 2d-view, we calculate the UL and DL beamforming effects by taking averages of the *normalised* matrices produced by the snapshots.

$$\overline{\overline{\left(\frac{\boldsymbol{R}_J^{DL}}{Tr\left(\boldsymbol{R}_J^{DL}\right)}\right)}} = \frac{1}{\#\ snapshots}\sum_{snapshots}\left(\frac{\boldsymbol{R}_J^{DL}}{Tr\left(\boldsymbol{R}_J^{DL}\right)}\right). \tag{91}$$

$$\overline{\overline{\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)}} = \frac{1}{\#\ snapshots}\sum_{snapshots}\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right). \tag{92}$$

$$\overline{\overline{\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)^{-1}}} = \frac{1}{\#\ snapshots}\sum_{snapshots}\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)^{-1}. \tag{93}$$

Note that the two average UL matrices $\overline{\overline{\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)}}$ and $\overline{\overline{\left(\frac{\boldsymbol{R}_J^{UL}}{Tr\left(\boldsymbol{R}_J^{UL}\right)}\right)^{-1}}}$ must be calculated separately since we cannot get one average matrix by inverting the other.

2.15.10 Switched Beamforming

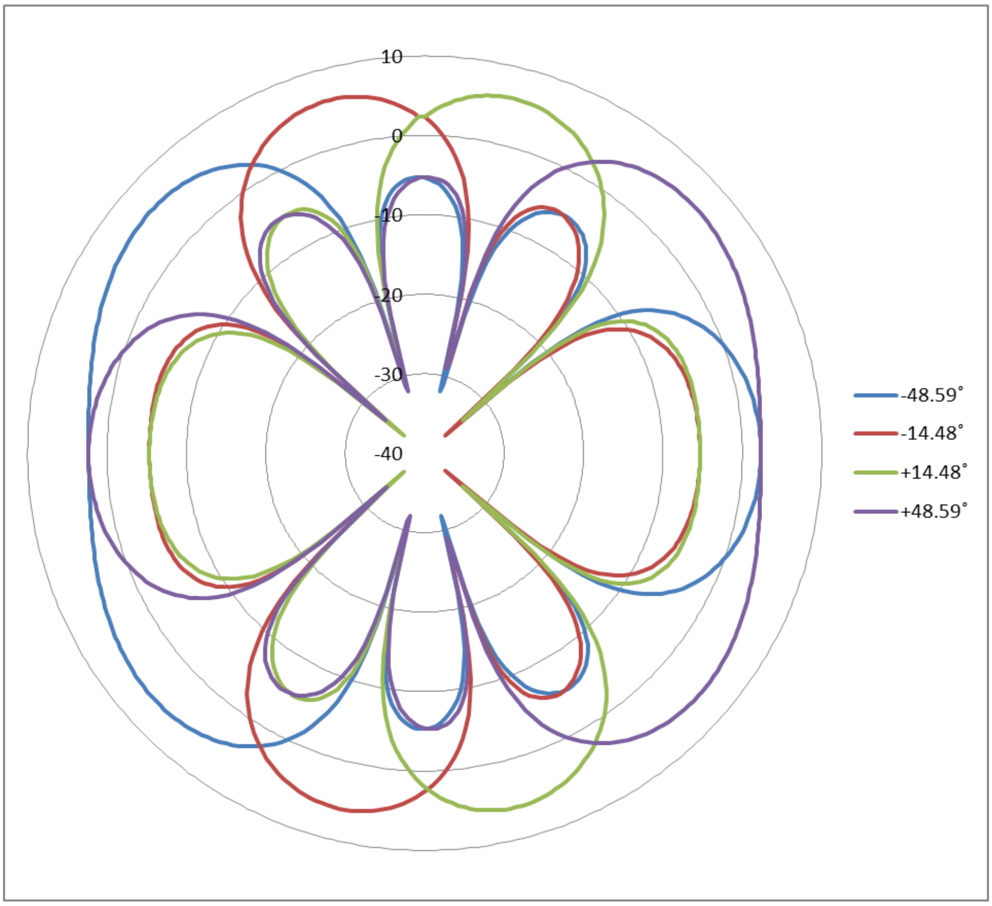
Some beamforming antennas use an analogue switched-beam approach, where a fixed passive network (e.g. Butler Matrix) in the antenna effectively provides a fixed set of beam weights and corresponding beam directions. As with adaptive beamforming, we treat all elements as having the same horizontal masking pattern, and can model the beamforming gains by taking the elements to be isotropic radiators without loss of generality.

We model an n-element switched-beam antenna as having a set of n fixed beamforming patterns with each beam direction (α_p) satisfying the relation:

$$\sin(\alpha_p) = \pm\frac{p}{n} \quad \text{where } p \text{ is an odd integer and} \quad 1 \le p \le (n-1). \tag{94}$$

The above relation causes the peak of the main lobe in each pattern to coincide with nulls in the other patterns.

Example: For n = 4, then $\sin(\alpha_p)$ can take the values ±1/4 and ±3/4. These give beam patterns with main lobes at ±14.48° and ±48.59° as shown in the next figure. Note that since we have considered isotropic elements, these angles do not include the effect of the horizontal mask. The beamforming patterns in the figure are showing where the *gain due to beamforming* will be strongest.



For a cell J and terminal k with azimuth $\theta_{J,k}$ with respect to the principal array direction we define the *quantised* steering vector $\overrightarrow{Q_k}$ as

$$\overrightarrow{Q_{J,k}} = \left(1\,,\; e^{\beta_{J,k}},\; e^{2\beta_{J,k}}\,,\,\ldots,\; e^{(n_J^{BF}-1)\beta_{J,k}}\right)^T \tag{95}$$

where

$$\beta_{J,k} = j\,\pi\;\mathrm{R}\left(n_J^{BF}\,\sin(\theta_{J,k})\right)/n_J^{BF} \tag{96}$$

where the function $\mathrm{R}(x)$ gives the nearest odd integer to x. The quantised steering vector $\overrightarrow{Q_{J,k}}$ corresponds to the switched beam that best matches the steering vector of the terminal ($S_{J,k}$).

2.15.11 Switched Beamforming: The Downlink

For adaptive beamforming, the matrix $\boldsymbol{R}_{J,k}^{DL}$ in (67) describes the azimuthal power distribution produced by a connection to a served terminal k. For switched beamforming, this matrix needs to be modified because power is steered towards the direction corresponding to $\overrightarrow{Q_{J,k}}$ rather than the direction corresponding to $\overrightarrow{S_{J,k}}$. So we use the following matrix instead

$$\boldsymbol{R}_{J,k}^{DL\ switched} = \left(P_{J,k}/n_J^{BF}\right) \overrightarrow{Q_{J,k}}\, \overrightarrow{Q_{J,k}}^H . \tag{97}$$

The DL received signal power for terminal k is then found by operating on this matrix with the steering vector for the terminal $(\overrightarrow{S_{J,k}})$ as follows

$$\overrightarrow{S_{J,k}}^H \boldsymbol{R}_{J,k}^{DL\ switched} \overrightarrow{S_{J,k}} = \left(P_{J,k}/n_J^{BF}\right)\left(\overrightarrow{S_{J,k}}^H \overrightarrow{Q_{J,k}}\, \overrightarrow{Q_{J,k}}^H \overrightarrow{S_{J,k}}\right) \tag{98}$$

and compared to the non-beamforming case we have the following DL signal (and DL SINR) gain due to beamforming

$$G_{J,k}^{DL\ SINR} = G_{J,k}^{DL\ Signal} = \left(\overrightarrow{S_{J,k}}^H \overrightarrow{Q_{J,k}}\, \overrightarrow{Q_{J,k}}^H \overrightarrow{S_{J,k}}\right) / n_J^{BF} . \tag{99}$$

Note that the numerator on the right is $\le \left(n_J^{BF}\right)^2$ so the maximum possible DL beamforming gain of n_J^{BF} now only occurs when the terminal coincides with one of the main switched-beam directions.

Similarly, when working out the effective interfering TX power radiated by a switched-beamforming antenna towards a victim terminal v, we operate on the *total DL TX power matrix for switched-beamforming* with the steering vector of the victim terminal $(\overrightarrow{S_{J,v}})$. So by analogy with (74) the interference power gain due to switched beamforming is given by

$$G_{J,v}^{DL\ BF} = \overrightarrow{S_{J,v}}^H \frac{\boldsymbol{R}_J^{DL\ switched}}{Tr\left(\boldsymbol{R}_J^{DL\ switched}\right)} \overrightarrow{S_{J,v}} \tag{100}$$

where

$$\boldsymbol{R}_J^{DL\ switched} = \sum_{k\in J} \boldsymbol{R}_{J,k}^{DL\ switched}. \tag{101}$$

Note that the only difference between the DL formulas for adaptive beamforming and switched-beamforming is that adaptive beamforming uses the DL power matrices $\boldsymbol{R}_{J,k}^{DL}$, while switched-beamforming uses the matrices $\boldsymbol{R}_{J,k}^{DL\ switched}$. Note these matrices have the same normalisation factor since

$$Tr\left(\boldsymbol{R}_J^{DL}\right) = Tr\left(\boldsymbol{R}_J^{DL\ switched}\right). \tag{102}$$

2.15.12 Switched Beamforming: The Uplink

The matrix $\boldsymbol{R}_J^{UL}$ given in (79) describes the spatial distribution of received power in the UL. This matrix is exactly the same for both adaptive and switched beamforming. What changes with switched beamforming is that the *weights* used in the UL become quantised and correspond to one of the switched beams.

2.15.13 Switched Beamforming: "Maximise UL Signal" Method

When using this method for a served terminal k, the UL weights for switched beamforming are given by

$$\overrightarrow{w_{J,k}}^{*} = \overrightarrow{Q_{J,k}}^{*}. \tag{103}$$

Substituting these into the expression for UL SINR in (78) and then comparing to the non-beamforming SINR in (82) gives the result

$$G_{J,k}^{UL\ SINR} = \left(\frac{\overrightarrow{Q_{J,k}}^{H} \boldsymbol{R}_{J,k}^{UL} \overrightarrow{Q_{J,k}}}{\overrightarrow{Q_{J,k}}^{H} \boldsymbol{R}_{J}^{UL} \overrightarrow{Q_{J,k}}} \right) / \left(\frac{P_{J,k}}{N + \sum_a P_a} \right) = \frac{1}{n_J^{BF}} \cdot \frac{\overrightarrow{Q_{J,k}}^{H} \overrightarrow{S_{J,k}} \overrightarrow{S_{J,k}}^{H} \overrightarrow{Q_{J,k}}}{\overrightarrow{Q_{J,k}}^{H} \frac{\boldsymbol{R}_{J}^{UL}}{Tr\left(\boldsymbol{R}_{J}^{UL}\right)} \overrightarrow{Q_{J,k}}}. \tag{104}$$

2.15.14 Switched Beamforming: "Maximise UL SINR" Method

This is similar to the "*Maximise UL Signal"* method for switched-beamforming described above. The difference is that instead of choosing the UL weights directly using (95) and (96), we test n_J^{BF} different sets of weights corresponding to the n_J^{BF} switched beams and choose the beam that gives the best UL SINR.

The n_J^{BF} switched beams are examined by considering each of the possible values of β in the set

$$\beta \in \left\{ -j\frac{\left(n_J^{BF}-1\right)\pi}{n_J^{BF}}, \dots, -j\frac{3\pi}{n_J^{BF}}, -j\frac{\pi}{n_J^{BF}}, j\frac{\pi}{n_J^{BF}}, j\frac{3\pi}{n_J^{BF}}, \dots, j\frac{\left(n_J^{BF}-1\right)\pi}{n_J^{BF}} \right\}. \tag{105}$$

For each value of β we have a quantised steering vector $\vec{Q}$ that describes the switched beam

$$\vec{Q} = \left(1, e^{\beta}, e^{2\beta}, \dots, e^{\left(n_J^{BF}-1\right)\beta}\right)^{T}. \tag{106}$$

As in (104), the corresponding beamforming gain for a served terminal k with steering vector $\overrightarrow{S_{J,k}}$ is then given by

$$G_{J,k}^{UL\ SINR} = \frac{1}{n_J^{BF}} \cdot \frac{\vec{Q}^{H} \overrightarrow{S_{J,k}} \overrightarrow{S_{J,k}}^{H} \vec{Q}}{\vec{Q}^{H} \frac{\boldsymbol{R}_{J}^{UL}}{Tr\left(\boldsymbol{R}_{J}^{UL}\right)} \vec{Q}}. \tag{107}$$

The beam whose value β maximises (107) is used to give the UL SINR gain. In the vast majority of cases this will be the exact same beam that maximises the UL signal power, and so the resulting UL SINR gain due to beamforming will match that of the *Maximise UL Signal* method.

2.15.15 Imperfect Beamforming

If the channel between the cell and the terminal has a large transmit angular spread (i.e. angles measured at the transmitting antenna) then this makes it harder for the cell to correctly determine the steering vector for the terminal. Consequently the DL beamforming gain is reduced because of errors in where the beam is steered, with the effect being more significant for arrays with more elements since these have narrower beams. The angular spread at the cell is ideally something that is returned by a propagation model. In the absence of this information, we allow the user to specify angular spread values based on the clutter type of the terminal, and then use a lookup table to reduce the DL beamforming gain accordingly.

2.15.16 UE-Specific Reference Signals

Beamforming in LTE requires UE-specific reference signals to be transmitted and this means the resource blocks allocated to a beamforming user will have fewer REs available for data since they are used for UE-specific RS instead. This overhead effectively increases the link activity of beamformed connections because more REs are consumed, and this is considered during the capacity checks for a terminal in the simulation snapshots.

2.15.17 Multi-Antenna Cells and ICIC

The beamforming parameters in the tool are specified at the cell level and so they apply to all antennas on the cell. This means that enabling beamforming on a cell enables it on all the antennas used by the cell, with the beamforming effects modelled separately for each child antenna. Note that we do not allow beamforming on repeaters, nor do we allow a beamformed link between a cell and its child repeater.

Similarly, if a cell is using ICIC it may split its carrier bandwidth into separate cell-centre (CC) and cell-edge (CE) partitions. If beamforming is enabled on such a cell then the beamforming will be modelled separately for the two partitions.

Example: If a cell has three antennas, and is using ICIC with both CC and CE partitions, then enabling beamforming on the cell will mean there are effectively 6 independent beamformers with their own set of UL and DL matrices.

2.16 Downlink Power and Noise Formulae

2.16.1 Downlink EPRE of Traffic, Control Channels and Signals

Useful and Total Symbol Time Definitions

$$T_p^{useful\ symbol} = \frac{1}{(\Delta f)_p}. \tag{108}$$

$T_p^{useful\ symbol}$ is the useful OFDMA symbol duration i.e. excluding the cyclic prefix (CP). It is determined purely by the subcarrier spacing $(\Delta f)_p$.

$$T_p^{full\ symbol} = \frac{T_p^{DL\ frame}}{\left(n_p^{DL\ subframes}\ n_p^{slots/subframe}\ n_p^{DL\ symbols/slot}\right)} = T_p^{useful\ symbol} + T_p^{CP}. \tag{109}$$

$T_p^{full\ symbol}$ and $T_p^{DL\ frame}$ represent the total OFDMA symbol duration (*including CP*) and DL frame duration respectively.

We can similarly define the useful frame time (i.e. excluding the CP) for the DL as follows.

$$T_p^{useful\ DL\ frame} = T_p^{DL\ frame}\left(\frac{T_p^{useful\ symbol}}{T_p^{full\ symbol}}\right). \tag{110}$$

DL Reference Signal EPRE

$$\varepsilon_{J,p}^{DLRS,tx} = \frac{P_J^{max}\ T_p^{useful\ DL\ frame}}{\left(\begin{array}{l} RE_p^{DLRS,tx} + RE_p^{BCH,tx}\ \delta_J^{BCH} + RE_p^{SCH,tx}\ \delta_J^{SCH} + \\ \quad + RE_p^{DL\ traffic,tx}\ \delta_J^{traffic} + RE_p^{CTRL,tx}\ \delta_J^{CTRL} \end{array}\right)}, \quad \textbf{(111)}$$

where $\varepsilon_{J,p}^{DLRS,tx}$ is the EPRE of the DLRS for cell J employing carrier p. P_J^{max} is the maximum transmission power of cell J.

DL Reference Signal PPRE

$$PPRE_{J,p}^{DLRS,tx} = \varepsilon_{J,p}^{DLRS,tx}\ (\Delta f)_p\ , \quad \textbf{(112)}$$

where $PPRE_{J,p}^{DLRS,tx}$ is the Power Per Resource Element of the DLRS for cell J employing carrier p.

DL Broadcast Channel EPRE

$$\varepsilon_{J,p}^{BCH,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{BCH}\ , \quad \textbf{(113)}$$

where $\varepsilon_{J,p}^{BCH,tx}$ is the EPRE of PBCH for cell J employing carrier p. The offset δ_J^{BCH} provides the ability to increase/decrease the PBCH EPRE with respect to DLRS EPRE.

DL Synchronization Channel EPRE

$$\varepsilon_{J,p}^{SCH,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{SCH}, \quad \textbf{(114)}$$

where $\varepsilon_{J,p}^{SCH,tx}$ is the EPRE of P-SCH and S-SCH for cell J employing carrier p. The offset δ_J^{SCH} provides the ability to increase/decrease the P-SCH and S-SCH EPRE with respect to DLRS EPRE.

DL BCH/SCH EPRE

$$\varepsilon_{J,p}^{BCH/SCH,tx} = \frac{\varepsilon_{J,p}^{BCH,tx}\ RE_p^{BCH,tx} + \varepsilon_{J,p}^{SCH,tx}\ RE_p^{SCH,tx}}{RE_p^{BCH,tx} + RE_p^{SCH,tx}}, \quad \textbf{(115)}$$

where $\varepsilon_{J,p}^{BCH/SCH,tx}$ is the combined EPRE of PBCH, P-SCH and S-SCH channels.

DL Control Channel EPRE

$$\varepsilon_{J,p}^{CTRL,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{CTRL}\ , \quad \textbf{(116)}$$

where $\varepsilon_{J,p}^{CTRL,tx}$ is the EPRE of PDCCH for cell J employing carrier p. The offset δ_J^{CTRL} provides the ability to increase/decrease the PDCCH EPRE with respect to DLRS EPRE. When using *Soft Frequency Reuse* or *Reuse partitioning* ICIC schemes, the respective CC and CE EPREs, i.e. $\varepsilon_{J,p,CC}^{CTRL,tx}$ and $\varepsilon_{J,p,CE}^{CTRL,tx}$ as given by (183) and (191) are employed in the CC and CE regions. Please refer to section 6 for complete details.

DL Traffic Channel EPRE

$$\varepsilon_{J,p}^{traffic,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{traffic}, \tag{117}$$

where $\varepsilon_{J,p}^{traffic,tx}$ is the EPRE of PDSCH for cell J employing carrier p. The offset $\delta_J^{traffic}$ provides the ability to increase/decrease the PDSCH EPRE with respect to DLRS EPRE. When using *Soft Frequency Reuse* or *Reuse partitioning* ICIC schemes, the respective CC and CE EPREs, i.e. $\varepsilon_{J,p,CC}^{traffic,tx}$ and $\varepsilon_{J,p,CE}^{traffic,tx}$ as given by (184) and (192) are employed in the CC and CE regions. Please refer to section 6 for complete details.

DL Traffic/Control EPRE

$$\varepsilon_{J,p}^{traffic/CTRL,tx} = \frac{\varepsilon_{J,p}^{traffic,tx}\ RE_p^{DL\ traffic,tx} + \varepsilon_{J,p}^{CTRL,tx}\ RE_p^{CTRL,tx}}{RE_p^{DL\ traffic,tx} + RE_p^{CTRL,tx}}, \tag{118}$$

where $\varepsilon_{J,p}^{traffic/CTRL,tx}$ is the combined EPRE of PDSCH/PDCCH channels. When using *Soft Frequency Reuse* or *Reuse partitioning* ICIC schemes, the respective CC and CE EPREs, i.e. $\varepsilon_{J,p,CC}^{traffic/CTRL,tx}$ and $\varepsilon_{J,p,CE}^{traffic/CTRL,tx}$ as given by (185) and (193) are employed in the CC and CE regions. Please refer to section 6 for complete details.

MBSFN DL Reference Signal EPRE

$$\varepsilon_{J,p}^{MBSFN\ RS,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{MBSFN\ RS}, \tag{119}$$

where $\varepsilon_{J,p}^{MBSFN\ RS,tx}$ is the EPRE of the MBSFN DL Reference Signal for cell J employing carrier p. The offset $\delta_J^{MBSFN\ RS}$ provides the ability to increase/decrease the EPRE with respect to DLRS EPRE.

MBSFN DL Reference Signal EPRE

$$\varepsilon_{J,p}^{MBSFN\ DATA,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{MBSFN\ DATA}, \tag{120}$$

where $\varepsilon_{J,p}^{MBSFN\ RS,tx}$ is the EPRE of the MBSFN DL Reference Signal for cell J employing carrier p. The offset $\delta_J^{MBSFN\ RS}$ provides the ability to increase/decrease the EPRE with respect to DLRS EPRE.

MBSFN Data EPRE

$$\varepsilon_{J,p}^{MBSFN\ DATA,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{MBSFN\ DATA}, \tag{121}$$

where $\varepsilon_{J,p}^{MBSFN\ DATA,tx}$ is the EPRE of the MBSFN DL Data channel for cell J employing carrier p. The offset $\delta_J^{MBSFN\ DATA}$ provides the ability to increase/decrease the EPRE with respect to DLRS EPRE.

MBSFN Ctrl EPRE

$$\varepsilon_{J,p}^{MBSFN\ CTRL,tx} = \varepsilon_{J,p}^{DLRS,tx}\ \delta_J^{MBSFN\ CTRL}, \tag{122}$$

where $\varepsilon_{J,p}^{MBSFN\ CTRL,tx}$ is the EPRE of the MBSFN DL Ctrl channel for cell J employing carrier p. The offset $\delta_J^{MBSFN\ CTRL}$ provides the ability to increase/decrease the EPRE with respect to DLRS EPRE.

2.16.2 Downlink Powers

DL Loss

$$L_{Jk}^{DL} = F(J,k,B)\left(L_{Jk}^{pathloss} L_{Jk}^{antenna} \frac{L_k^{body} L_J^{feeder} L_J^{mha}}{G_J^{antenna} G_J^{DL\ corr.} G_k^{antenna} G_k^{Rx\ Comb}}\right) \qquad \textbf{(123)}$$

The term $L_J^{mha}$is Mast Head Amplifier Insertion Loss as specified on the MHA equipment. The terms $L_{Jk}^{pathloss}$and $L_{Jk}^{antenna}$ are read from the prediction file. $F(J,k,B)$ is the selector function that depends on the directional antenna capabilities of the terminal k and is given by:

$$F(J,k,B) = \begin{cases} 1, & \text{if } |\theta| \le \frac{\Delta_k}{2} \\ \infty, & \text{otherwise} \end{cases}, \qquad \textbf{(124)}$$

where Δ_k is the beamwidth of the terminal antenna. The azimuth of terminal antenna is always assumed to be pointing towards the serving/best server (sector B). The angle θ is the bearing of the cell of interest (sector J) as depicted in the Fig.6 below.

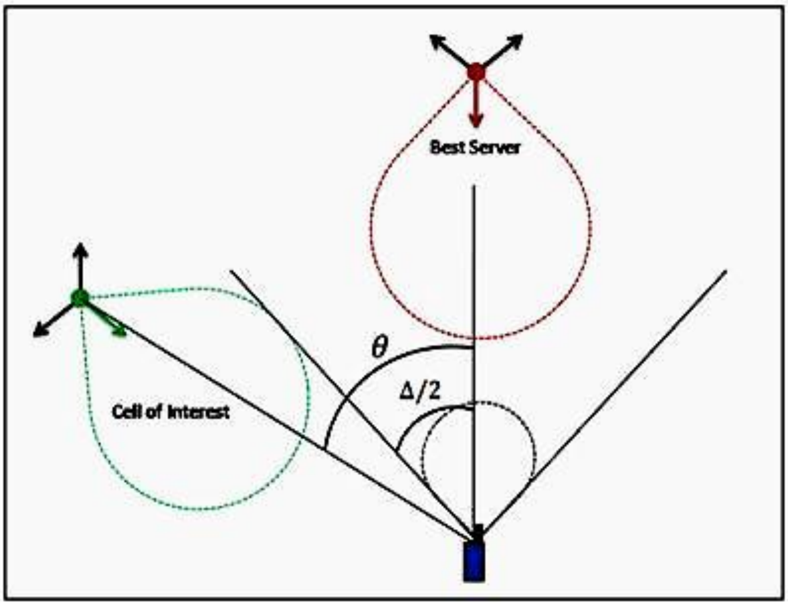


Figure 11: Modelling of directional antennas on Terminal

DL Reference Signal Power (*Instantaneous*)

$$P_{J,p}^{DLRS,tx} = \varepsilon_{J,p}^{DLRS,tx}\, n_p^{RB}\, n_p^{DLRS\ SC/\ RB,tx}\left(\frac{1}{T_p^{useful\ symbol}}\right) \qquad \textbf{(125)}$$

where $P_{J,p}^{DLRS,tx}$ is the instantaneous DLRS power. $\varepsilon_{J,p}^{DLRS,tx}$ is the EPRE of DLRS for cell J employing carrier p as given in (111). The DLRS is transmitted over n_p^{RB} resource blocks. When summed over all TXs, the DLRS uses a total of of $n_p^{DLRS\ SC/RB,tx}$ subcarriers per resource block as given by

$$n_p^{DLRS\ SC/\ RB\ ,tx} = \begin{cases} n_p^{DLRS\ SC/\ RB} & \text{when } tx = 1 \\ 2\ \times n_p^{DLRS\ SC/\ RB} & \text{when } tx > 1 \end{cases}. \qquad \textbf{(126)}$$

Finally $T_p^{useful\ symbol}$ is the useful OFDMA symbol duration given by (108).

DL EiRP (Reference Signal) per RE

$$(EiRP)_{J,p}^{DLRS,tx} = \varepsilon_{J,p}^{DLRS,tx} \frac{G_J^{DL\,corr} \ G_J^{antenna}}{L_J^{feeder} \ L_J^{mha}} \left(\frac{1}{T_p^{useful\ symbol}}\right), \tag{127}$$

where $(EiRP)_{J,p}^{DLRS,tx}$ is the DL EiRP per Reference Signal RE, for cell J employing carrier p.

DL EiRP Total Max

$$(EiRP)_{J,p}^{Total\ Max} = \frac{G_J^{DL\,corr} \ G_J^{antenna}}{L_J^{feeder} \ L_J^{mha}} \ P_J^{max}, \tag{128}$$

where $(EiRP)_{J,p}^{Total\ Max}$ is the DL EiRP, for cell J employing carrier p and transmitting at full power.

DL Broadcast Channel Power (*Instantaneous*)

$$P_{J,p}^{BCH,tx} = \varepsilon_{J,p}^{BCH,tx} \ n_p^{BCH\ RB} \ n_p^{DL\ SC/\ RB} \left(\frac{1}{T_p^{useful\ symbol}}\right), \tag{129}$$

where $P_{J,p}^{BCH,tx}$ is the instantaneous PBCH power. $\varepsilon_{J,p}^{BCH,tx}$ is the EPRE of PBCH for cell J employing carrier p as given in (113). The PBCH is transmitted using the central 6 resource blocks as defined by $n_p^{BCH\ RB}$ employing all subcarriers in each resource block as given by $n_p^{DL\ SC/RB}$.

DL Synchronization Channel Power (*Instantaneous*)

$$P_{J,p}^{SCH,tx} = \varepsilon_{J,p}^{SCH,tx} \ n_p^{SCH\ RB} \ n_p^{DL\ SC/\ RB} \left(\frac{1}{T_p^{useful\ symbol}}\right), \tag{130}$$

where $P_{J,p}^{SCH,tx}$ is the instantaneous P-SCH and S-SCH power. $\varepsilon_{J,p}^{SCH,tx}$ is the EPRE of P-SCH and S-SCH for cell J employing carrier p as given in (114). The synchroniztion channels are transmitted using the central 6 resource blocks as defined by $n_p^{SCH\ RB}$ employing all subcarriers in each resource block as given by $n_p^{DL\ SC/RB}$.

DL Control Channel Power At Full Load (*Averaged over frame*)

$$P_{J,p}^{CTRL,tx} = \varepsilon_{J,p}^{CTRL,tx} \ RE_{J,p}^{CTRL,tx} \left(\frac{1}{T_p^{useful\ DL\ frame}}\right), \tag{131}$$

where $P_{J,p}^{CTRL,tx}$ is the average Control power of cell J employing carrier p. $\varepsilon_{J,p}^{CTRL,tx}$ is the EPRE of PDCCH+PCFICH+PHICH for cell J employing carrier p as given in (116). As the number of symbols/ resource blocks employed by Control channels i.e. PDCCH+PCFICH+PHICH varies over time, an average value has been considered. The useful DL frame time $T_p^{useful\ DL\ frame}$ is given by (110). The above value assumes the cell has no ABS subframes or MBSFN subframes.

DL Traffic Channel Power At Full Load (*Averaged over frame*)

$$P_{J,p}^{traffic,tx} = \varepsilon_{J,p}^{traffic,tx} \ RE_{J,p}^{traffic,tx} \left(\frac{1}{T_p^{useful\ DL\ frame}}\right), \tag{132}$$

where $P_{J,p}^{traffic,tx}$ is the average traffic i.e. PDSCH power of cell J employing carrier p. $\varepsilon_{J,p}^{traffic,tx}$ is the EPRE of PDSCH for cell J employing carrier p as given in (117). As the number of symbols/resource blocks employed by traffic varies over time, an average value has been considered. The useful DL frame time $T_p^{useful\ DL\ frame}$ is given by (110). The above value assumes the cell has no ABS subframes or MBSFN subframes.

2.16.3 Downlink Thermal Noise

DL Thermal Noise Power (over whole DL bandwidth)

$$N_{p,k}^{DL} = K\ T\ W_p^{DL}\ \eta_{p,k} \quad , \tag{133}$$

where $N_{p,k}^{DL}$ is the DL thermal noise power over the whole DL bandwidth, and $\eta_{p,k}$ is the thermal noise figure of terminal k. The DL bandwidth W_p^{DL} of carrier p is given by

$$W_p^{DL} = n_p^{DL\ SC/RB}\ n_p^{RB}\ (\Delta f)_p \quad . \tag{134}$$

DL Thermal Noise Power Per RE

$$N_{p,k}^{DL\ RE} = K\ T\ (\Delta f)_p\ \eta_{p,k} \quad , \tag{135}$$

where $N_{p,k}^{DL\ RE}$ is the DL thermal noise power of a single resource element, and $\eta_{p,k}$ is the thermal noise figure of terminal k. $(\Delta f)_p$ is the subcarrier spacing.

DL Thermal Noise EPRE

$$\bar{N}_{p,k}^{DL\ RE} = K\ T\ \eta_{p,k} \quad , \tag{136}$$

where $\bar{N}_{p,k}^{DL\ RE}$ is the DL thermal noise EPRE, and $\eta_{p,k}$ is the thermal noise figure of terminal k.

2.16.4 Downlink Received Interference

DL Total Average Transmitted Useful Energy per Frame

RSSI is measured over the OFDMA symbols that contain reference symbols. For interfering cell J, the mean transmitted energy $E_{J,p}^{DL\ total,tx}$ in one of these OFDMA symbols (summed over all antenna ports) is given by

$$E_{J,p}^{DL\ total,tx} = \begin{matrix} \varepsilon_{J,p}^{DLRS,tx}\ n_p^{RB}\ n_p^{DLRS\ SC/\ RB\ ,tx} + \\ \varepsilon_{J,p}^{traffic/CTRL,tx}\ U_J\ n_p^{RB}\left(n_p^{DL\ SC/\ RB} - n_p^{DLRS\ SC/\ RB\ ,tx}\right) \end{matrix} , \tag{137}$$

The traffic and control energy is scaled by U_J which is the mean downlink load of cell J. When cell J is using *Soft Frequency Reuse* or *Reuse Partitioning* ICIC schemes, the traffic and control energy can be broken down into components for its CC and CE zones as follows

$$\varepsilon_{J,p}^{traffic/CTRL,tx}\ U_J = \gamma_p^{CC}\left(\varepsilon_{J,p,CC}^{traffic/CTRL,tx}\ U_J^{CC}\right) + \gamma_p^{CE}\left(\varepsilon_{J,p,CE}^{traffic/CTRL,tx}\ U_J^{CE}\right) \quad . \tag{138}$$

The factors γ_p^{CC} and γ_p^{CE} for carrier p are the downlink CC and CE zone bandwidths divided by the downlink carrier bandwidth. Please see section 6 for complete details on ICIC. The number of resource blocks is given by n_p^{RB}. When summed over all TXs, the DLRS uses a total of $n_p^{DLRS\,SC/RB,tx}$ subcarriers per resource block as given by

$$n_p^{DLRS\,SC/\,RB\,,tx} = \begin{cases} n_p^{DLRS\,SC/\,RB} & \text{when } tx = 1 \\ 2\,\times n_p^{DLRS\,SC/\,RB} & \text{when } tx > 1 \end{cases} . \quad \textbf{(139)}$$

The mean received interfering power for the RSSI calculation $P_{J,p,k}^{DL\,total,tx}$ is then given by

$$P_{J,p,k}^{DL\,total,tx} = \frac{E_{J,p}^{DL\,total,tx}}{L_{Jk}^{DL}}\left(\frac{1}{T_p^{useful\,symbol}}\right), \quad \textbf{(140)}$$

where the useful OFDMA symbol duration $T_p^{useful\,symbol}$ is given by (108).

DL BCH/SCH Received Interference EPRE

$$I_{J,p,k}^{BCH/SCH,tx} = \sum_q \left(O_{pq}^{freq} W_q/W_p\right) \sum_{C\neq J} \frac{\varepsilon_{C,q}^{BCH/SCH,tx}}{L_{Ck}^{DL}} \quad , \quad \textbf{(141)}$$

where $I_{J,p,k}^{BCH/SCH,tx}$ is the received DL interference EPRE from PBCH, P-SCH and S-SCH channels used in the DL BCH/SCH SINR calculation given in (169). $\left(O_{pq}^{freq} W_q/W_p\right)$ is the frequency overlap factor for mapping EPRE from the aggressor carrier q to the victim carrier p as given by (49).

DLRS Received Interference EPRE

This forms part of the denominator in the DLRS SINR calculation given in (168). The interfering EPRE is given by the general formula for $I_{J,p,k}^{v\in V}$ in (51) with an appropriate choice of victim resource element type v and victim subframe type V.

$$I_{J,p,k}^{DLRS\,,tx} = I_{J,p,k}^{v\in V} \quad \text{with } v = \text{“Unicast DLRS” and } V = \text{“DL Unicast (ABS and non-ABS)”} \quad \textbf{(142)}$$

When an interfering cell C is using *Soft Frequency Reuse* or *Reuse Partitioning* ICIC schemes, the mean interfering EPRE from its traffic and control channels is a weighted sum of values for its CC and CE zones as follows

$$\varepsilon_{C,q}^{traffic/CTRL,tx}\, U_C = \gamma_q^{CC}\left(\varepsilon_{C,q,CC}^{traffic/CTRL,tx}\, U_C^{CC}\right) + \gamma_q^{CE}\left(\varepsilon_{C,q,CE}^{traffic/CTRL,tx}\, U_C^{CE}\right) . \quad \textbf{(143)}$$

The factors γ_q^{CC} and γ_q^{CE} for carrier q are the downlink CC and CE zone bandwidths divided by the downlink carrier bandwidth, and U_C^{CC} and U_C^{CE} are the DL load factors for the two zones. Please see section 6 for complete details on ICIC.

DL Traffic and Control Received Interference EPRE

This forms part of the denominator in the DL Traffic/Ctrl SINR calculation given in (170). The interfering EPRE is given by the general formula for $I_{J,p,k}^{v\in V}$ in (51) with an appropriate choice of victim resource element type v and victim subframe type V.

$$I_{J,p,k}^{traffic/CTRL\,,tx} = I_{J,p,k}^{v\in V} \quad \text{with } v = \text{“Unicast Traffic/Ctrl” and } V = \text{“DL Unicast (non-ABS)”} \quad \textbf{(144)}$$

When an interfering cell C is using *Soft Frequency Reuse* or *Reuse Partitioning* ICIC schemes, its interfering traffic and control energy can be broken down into components from its CC and CE zones as given by (143).

If the interfering cell and victim cell both use ICIC and have the same carrier, then the CC and CE interference components only affect the respective zones of the victim.

DL Control Received Interference EPRE

This forms part of the denominator in the DL Ctrl SINR calculation given in (171). The interfering EPRE is given by the general formula for $I_{J,p,k}^{v \in V}$ in (51) with an appropriate choice of victim resource element type v and victim subframe type V.

$$I_{J,p,k}^{CTRL,tx} = I_{J,p,k}^{v \in V} \quad \text{with } v = \text{“Unicast Ctrl” and } V = \text{“DL Unicast (non-ABS)”} \tag{145}$$

When an interfering cell C is using *Soft Frequency Reuse* or *Reuse Partitioning* ICIC schemes, its interfering control energy can be broken down into components from its CC and CE zones as follows

$$\varepsilon_{C,q}^{CTRL,tx} \, U_C = \gamma_q^{CC} \left(\varepsilon_{C,q,CC}^{CTRL,tx} \, U_C^{CC} \right) + \gamma_q^{CE} \left(\varepsilon_{C,q,CE}^{CTRL,tx} \, U_C^{CE} \right) . \tag{146}$$

The factors γ_q^{CC} and γ_q^{CE} for carrier q are the downlink CC and CE zone bandwidths divided by the downlink carrier bandwidth, and U_C^{CC} and U_C^{CE} are the DL load factors for the two zones. Please see section 6 for complete details on ICIC.

If the interfering cell and victim cell both use ICIC and have the same carrier, then the CC and CE interference components only affect the respective zones of the victim.

DL Traffic Received Interference EPRE

This forms part of the denominator in the DL Traffic SINR calculation given in (172). The interfering EPRE is given by the general formula for $I_{J,p,k}^{v \in V}$ in (51) with an appropriate choice of victim resource element type v and victim subframe type V.

$$I_{J,p,k}^{traffic,tx} = I_{J,p,k}^{v \in V} \quad \text{with } v = \text{“Unicast Traffic” and } V = \text{“DL Unicast (non-ABS)”} \tag{147}$$

When an interfering cell C is using *Soft Frequency Reuse* or *Reuse Partitioning* ICIC schemes, its interfering traffic energy can be broken down into components from its CC and CE zones as follows

$$\varepsilon_{C,q}^{traffic,tx} \, U_C = \gamma_q^{CC} \left(\varepsilon_{C,q,CC}^{traffic,tx} \, U_C^{CC} \right) + \gamma_q^{CE} \left(\varepsilon_{C,q,CE}^{traffic,tx} \, U_C^{CE} \right) . \tag{148}$$

The factors γ_q^{CC} and γ_q^{CE} for carrier q are the downlink CC and CE zone bandwidths divided by the downlink carrier bandwidth, and U_C^{CC} and U_C^{CE} are the DL load factors for the two zones. Please see section 6 for complete details on ICIC.

If the interfering cell and victim cell both use ICIC and have the same carrier, then the CC and CE interference components only affect the respective zones of the victim.

2.17 UPLINK POWER AND NOISE FORMULAE

UL Loss

$$L_{Jk}^{UL} = F(J,k,B)\left(L_{Jk}^{pathloss} L_{Jk}^{antenna} \frac{L_k^{body}\ L_J^{feeder}}{G_J^{antenna}\ G_J^{UL\,corr}\ G_k^{antenna}\ G_J^{mha}}\right). \qquad \textbf{(149)}$$

The terms $L_{Jk}^{pathloss}$and $L_{Jk}^{antenna}$ are read from the prediction file. $F(J,k,B)$ is the selector function that depends on the directional antenna capabilities of the terminal k and is given by (124). G_J^{mha} is read form the Antennas tab of the LTE cell.

2.17.1 Uplink Thermal Noise

UL Thermal Noise Power (over whole UL bandwidth)

$$N_{J,p}^{UL} = K\ T\ W_p^{UL}\ \eta_{J,p}\ , \qquad \textbf{(150)}$$

where $N_{J,p}^{UL}$ is the UL thermal noise power over the whole UL bandwidth. $\eta_{J,p}$ is the thermal noise figure of cell J. The UL bandwidth W_p^{UL} of carrier p is given by

$$W_p^{UL} = n_p^{UL\ SC/RB}\ n_p^{RB}\ (\Delta f)_p\ . \qquad \textbf{(151)}$$

2.17.2 Uplink Received Interference and Required TX Power

UL Received Interference

In LTE, intra-cell terminals are perfectly orthogonal and the UL received interference only comes from out-of-cell terminals. The received UL interference power on cell J is given by summing the power received from terminals served by other cells C as follows

$$I_{J,p}^{UL} = \sum_q \sum_{C\neq J} \sum_{k\in C} O_{pq}^{freq} \cdot O_{A\in C\to V\in J}^{time} \cdot \frac{P_{k,A\in C,q}^{average}\ \Theta_{JC}^{ICIC}}{L_{Jk}^{UL}}\ , \qquad \textbf{(152)}$$

where $I_{J,p}^{UL}$ is the UL received (inter-cell) interference captured by the whole UL carrier bandwidth.

The frequency-overlap factor O_{pq}^{freq} maps power from the aggressor carrier bandwidth to the victim carrier bandwidth.

The time-overlap factor $O_{A\in C\to V\in J}^{time}$ accounts for any eICIC effects between cells J and C, as well as accounting for any other differences between subframe sequences on the two cells.

The victim and aggressor subframe types (V and A) in (152) are restricted to *non-ABS UL unicast subframes* since these are the only subframe types in which UL power is transmitted by the terminal or received by the cell. So the quantity $P_{k,A\in C,q}^{average}$ represents the average UL TX power for terminal k in one of its serving cell's UL non-ABS subframes, and the quantity $I_{V\in J,p}^{UL}$ represents the UL RX power for victim cell J in one of its UL non-ABS subframes.

The factor Θ_{JC}^{ICIC} is the (frequency-based) *ICIC factor* and is only applicable when cells J and C are both using the same carrier and ICIC scheme. ICIC schemes as explained in chapter 6.

UL Interference Level

$$(Interference\ Level)_{J,p} = \frac{I_{J,p}^{UL} + N_{J,p}^{UL}}{N_{J,p}^{UL}}\ , \tag{153}$$

where $N_{J,p}^{UL}$ is the UL thermal noise over the whole UL bandwidth as given by (150).

UL Bandwidth Allocation Method

The following describes the UL calculation for a terminal k served by beam i on cell J using carrier p. The calculation depends on the selected UL bandwidth allocation method, which determines the number of resource blocks over which a terminal is instantaneously attempting to transmit. For a fixed TX power, increasing the number of allocated resource blocks will lower the TX power spectral density and therefore lower the achieved SINR. We first define the two quantities $n_p^{minimum\_RB}$ and $n_p^{maximum\_RB}$ on carrier p.

$$n_p^{minimum\_RB} = \left\lceil n_p^{RB}\ \alpha_p^{UL\ bearer} \right\rceil. \tag{154}$$

$n_p^{minimum\_RB}$ is the minimum number of resource blocks over which the terminal can spread its transmission power while still meeting the required bearer resource consumption ($\alpha_p^{UL\ bearer}$).

$$n_p^{maximum\_RB} = \min\left(n_p^{RB}, \left\lfloor \frac{\left(P_k^{max} / L_{Ji,k}^{UL}\right)}{SINR_{req}^{UL\ bearer}\ \left(I_{Ji,p}^{UL} + N_{J,p}^{UL}\right)} \right\rfloor\right). \tag{155}$$

$n_p^{maximum\_RB}$ is the maximum number of resource blocks over which the terminal can spread its transmission power (P_k^{max}) while still satisfying the SINR requirement of the bearer ($SINR_{req}^{UL\ bearer}$). This SINR requirement is modified depending on whether the connection makes use of an Advanced Antenna System (AAS) as explained in section 7.

- **Use Minimum Resource Blocks**

This method allocates the minimum number of resource blocks, so

$$n_p^{allocated\ RB} = n_p^{minimum\_RB}. \tag{156}$$

- **Use All Resource Blocks**

This method allocates all resource blocks, so

$$n_p^{allocated\ RB} = n_p^{RB}. \tag{157}$$

- **Maintain Connection**

This method allocates as many resource blocks as possible while still maintaining coverage, so

$$n_p^{allocated\ RB} = \min\left[n_p^{RB}, \max\left(n_p^{minimum\_RB}, n_p^{maximum\_RB}\right)\right]. \tag{158}$$

The number of instaneasouly alocated resource blocks, $n_p^{allocated\ RB}$, is used to check if a terminal can meet the SINR requirement of the evaluated UL bearer, when tranmistting at maximum power.

The number of allocated resource blocks is also restricted by the ICIC schemes, if in use. This is a result of n_p^{RB} being restricted for either cell centre or cell edge area. See Chapter 6 Inter Cell Interference Coordination.

UL Required TX Power

The UL required TX power of terminal k served by cell J using carrier p is given by

$$P_{p,k}^{req} = SINR_{req}^{UL\,bearer}\left(I_{J,p}^{UL} + N_{J,p}^{UL}\right) L_{Jk}^{UL}\,\frac{n_p^{allocated\ RB}}{n_p^{RB}}, \qquad \textbf{(159)}$$

where the terminal spreads its power over $n_p^{allocated\ RB}$ resource blocks according to the relevant bandwidth allocation method as given by (156) to (158). $SINR_{req}^{UL\,bearer}$ is the SINR requirement of the UL bearer. This SINR requirement is modified depending on whether the connection makes use of an Advanced Antenna System (AAS) as explained in section 8. For example, if UL beamforming is being used then the SINR requirement would be scaled down by a factor of $G_{J,k}^{UL\,SINR}$ (the UL SINR gain due to beamforming).

The actual transmit power of the terminal ($P_{p,k}^{PC}$) is restricted to the dynamic range of the terminal, so the peak UL TX power is given by

$$P_{p,k}^{PC} = \max\left(P_k^{min}, P_{p,k}^{req}\right), \qquad \textbf{(160)}$$

where P_k^{max} and P_k^{min} are the maximum and minimum power of terminal k with

$$P_k^{min} = \frac{P_k^{max}}{D_k}, \qquad \textbf{(161)}$$

where D_k is the dynamic range of the transmit power.

The time average UL TX power is given by

$$P_{p,k}^{average} = P_{p,k}^{PC}\,\alpha_p^{UL\,bearer} \times \frac{n_p^{RB}}{n_p^{allocated\ RB}}. \qquad \textbf{(162)}$$

UL SINR Margin

The UL SINR margin in dB is defined as

$$P_{p,k}^{margin} = 10\log_{10}\left(\frac{P_k^{max}}{P_{p,k}^{req}}\right). \qquad \textbf{(163)}$$

2.18 Link Budget Formulae

DL Reference Signal Received Power (RSRP)

$$(RSRP)_{J,p,k}^{tx} = \frac{\varepsilon_{J,p}^{DLRS,tx}}{L_{Jk}^{DL}} \left(\frac{1}{T_p^{useful\ symbol}} \right) = \frac{PPRE_{J,p}^{DLRS,tx}}{L_{Jk}^{DL}} \tag{164}$$

where $(RSRP)_{J,p,k}^{tx}$ is the DL RSRP for cell J employing carrier p and at the terminal k and is defined as the linear average over the power contributions (in Watts) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth.

RSSI

The unicast RSSI is given by the general formula for $(RSSI)_{J,p,k}^{V}$ in (50) with an appropriate choice of victim subframe type V.

$$(RSSI)_{p,k} = (RSSI)_{J,p,k}^{V} \qquad \text{with } V = \text{“DL Unicast (ABS and non-ABS)”} \tag{165}$$

DL Reference Signal Received Quality (RSRQ)

$$(RSRQ)_{J,p,k}^{tx} = \frac{n_p^{RB}\ (RSRP)_{J,p,k}^{tx}}{(RSSI)_{p,k}}, \tag{166}$$

where $(RSRQ)_{J,p,k}^{tx}$ is the DL RSRQ for cell J employing carrier p and at the terminal k. The denominator $(RSSI)_{p,k}$ comprises the linear average of the total received power in the measurement bandwidth, over n_p^{RB} number of resource blocks by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise etc. as given by (165).

DL Reference Signal SNR

$$(SNR)_{J,p,k}^{DLRS,tx} = \frac{(RSRP)_{J,p,k}^{tx}}{N_{p,k}^{DL\ RE}}, \tag{167}$$

where $(SNR)_{J,p,k}^{DLRS,tx}$ is the DLRS SNR for cell J employing carrier p and at the terminal k. $N_{p,k}^{DL\ RE}$ is the DL thermal noise power of a single RE as given by (135).

DL Reference Signal SINR

$$(SINR)_{J,p,k}^{DLRS,tx} = \frac{\varepsilon_{J,p}^{DLRS,tx}}{L_{Jk}^{DL}\left(\bar{N}_{p,k}^{DL\ RE} + I_{J,p,k}^{DLRS,tx}\right)}, \tag{168}$$

where $(SINR)_{J,p,k}^{DLRS,tx}$ is the DLRS $SINR$ for cell J employing carrier p and at the terminal k. $\bar{N}_{p,k}^{DL\ RE}$ is the DL thermal noise EPRE as given by (136). $I_{J,p,k}^{DLRS,tx}$ is the DLRS received interference EPRE as given by (142).

DL BCH/SCH SINR

$$(SINR)_{J,p,k}^{BCH/SCH,tx} = \frac{\varepsilon_{J,p}^{BCH/SCH,tx}}{L_{Jk}^{DL}\left(\bar{N}_{p,k}^{DL\,RE} + I_{J,p,k}^{BCH/SCH,tx}\right)} \quad , \tag{169}$$

where $(SINR)_{J,p,k}^{BCH/SCH,tx}$ is the DL PBCH /P-SCH+S-SCH $SINR$ for cell J employing carrier p and at the terminal k. $\bar{N}_{p,k}^{DL\,RE}$ is the DL thermal noise EPRE as given by (136). $I_{J,p,k}^{BCH/SCH,tx}$ is the DL PBCH/P-SCH+S-SCH received interference EPRE as given by (141).

DL Traffic/Ctrl SINR

$$(SINR)_{J,p,k}^{traffic/CTRL,tx} = \frac{\varepsilon_{J,p}^{traffic/CTRL,tx}\ G_{J,k}^{DL\,Signal}}{L_{Jk}^{DL}\left(\bar{N}_{p,k}^{DL\,RE} + I_{J,p,k}^{traffic/CTRL,tx}\right)} \quad , \tag{170}$$

where $(SINR)_{J,p,k}^{traffic/CTRL,tx}$ is the PDSCH/PDCCH $SINR$ for cell J employing carrier p and at the terminal k. Note that the factor $G_{J,k}^{DL\,Signal}$ only applies if the terminal is served by DL beamforming. $\bar{N}_{p,k}^{DL\,RE}$ is the DL thermal noise EPRE as given by (136). $I_{J,p,k}^{traffic/CTRL,tx}$ is the DL PDSCH/PDCCH received interference EPRE as given by (144), while $\varepsilon_{J,p}^{traffic/Ctrl,tx}$ is given by (118). When using *Soft Frequency Reuse* or *Reuse partitioning* ICIC schemes, the respective CC and CE EPREs, i.e. $\varepsilon_{J,p,CC}^{traffic/CTRL,tx}$ and $\varepsilon_{J,p,CE}^{traffic/CTRL,tx}$ as given by (185) and (193) are employed in the CC and CE regions. Please refer to section 6 for complete details.
The value of $(SINR)_{J,p,k}^{traffic/CTRL,tx}$ is compared against $SINR_{req}^{DL\,bearer}$ during bearer connections scenarios. Please refer to section 4 for complete details.

DL Ctrl SINR

$$(SINR)_{J,p,k}^{CTRL,tx} = \frac{\varepsilon_{J,p}^{CTRL,tx}\ G_{J,k}^{DL\,Signal}}{L_{Jk}^{DL}\left(\bar{N}_{p,k}^{DL\,RE} + I_{J,p,k}^{CTRL,tx}\right)} \quad , \tag{171}$$

where $(SINR)_{J,p,k}^{CTRL,tx}$ is the PDCCH $SINR$ for cell J employing carrier p and at the terminal k. Note that the factor $G_{J,k}^{DL\,Signal}$ only applies if the terminal is served by DL beamforming. $\bar{N}_{p,k}^{DL\,RE}$ is the DL thermal noise EPRE as given by (136). $I_{J,p,k}^{CTRL,tx}$ is the DL PDCCH received interference EPRE as given by (145). When using *Soft Frequency Reuse* or *Reuse partitioning* ICIC schemes, the respective CC and CE EPREs, i.e. $\varepsilon_{J,p,CC}^{CTRL,tx}$ and $\varepsilon_{J,p,CE}^{CTRL,tx}$ as given by (183) and (191) are employed in the CC and CE regions. Please refer to section 6 for complete details.

DL Traffic SINR

$$(SINR)_{J,p,k}^{traffic,tx} = \frac{\varepsilon_{J,p}^{traffic,tx}\ G_{J,k}^{DL\ Signal}}{L_{Jk}^{DL}\ \left(\bar{N}_{p,k}^{DL\ RE}\ +\ I_{J,p,k}^{traffic,tx}\right)}\ \ , \tag{172}$$

where $(SINR)_{J,p,k}^{traffic,tx}$ is the PDSCH $SINR$ for cell J employing carrier p and at the terminal k. Note that the factor $G_{J,k}^{DL\ Signal}$ only applies if the terminal is served by DL beamforming. $\bar{N}_{p,k}^{DL\ RE}$ is the DL thermal noise EPRE as given by (136). $I_{J,p,k}^{traffic,tx}$ is the DL PDSCH received interference EPRE as given by (147). When using *Soft Frequency Reuse* or *Reuse partitioning* ICIC schemes, the respective CC and CE EPREs, i.e. $\varepsilon_{J,p,CC}^{traffic,tx}$ and $\varepsilon_{J,p,CE}^{traffic,tx}$ as given by (184) and (192) are employed in the CC and CE regions. Please refer to section 6 for complete details.

UL Traffic/Ctrl SINR (Power Controlled)

$$(SINR)_{Jp,k}^{UL\ traffic/CTRL,PC} = \frac{\left(P_{p,k}^{PC}/L_{Jk}^{UL}\right)}{\left(I_{J,p}^{UL}\ +\ N_{J,p}^{UL}\right)} \times \frac{n_p^{RB}}{n_p^{allocated\ RB}}, \tag{173}$$

where $(SINR)_{J,p,k}^{UL\ traffic/CTRL,PC}$ is the UL PUSCH/PUCCH power controlled $SINR$. This is calculated by using the power controlled TX power $P_{p,k}^{PC}\ =\ \max\left(P_k^{min}, P_{p,k}^{req}\right)$ of terminal k which is enough to meet the UL SINR requirement $SINR_{req}^{UL\ bearer}$ of the achievable UL bearer at a given location. See (159) to (162). $(SINR)_{J,p,k}^{UL\ traffic/CTRL,PC}$ is compared against $SINR_{req}^{UL\ bearer}$ during bearer connections scenarios.

3 SNAPSHOT OVERVIEW

The key purpose of a snapshot is to provide us with measures of system load for a particular distribution of terminals. To obtain these measures of system load, we must calculate uplink and downlink transmission powers for all the links in the system. A snapshot involves the following stages:

- Creating a random terminal distribution.
- Setting random terminal parameters (speeds, shadow fades and etc.)
- Calculating link powers using *Power Iterations*
- Gathering results

3.1 RANDOM TERMINAL DISTRIBUTION

The first stage of a snapshot involves creating a random distribution of terminals representing the offered traffic in the network. The spatial distribution of terminals must be random, but more importantly it must be *unbiased*. In other words, it must be reasonable compared to the terminal density array provided by the user. To see how this can be achieved, we need to consider a single pixel (bin) in the simulation.

Consider a pixel that has a terminal density of D terminal/km^2 and an area of A km^2, so that the average number of terminals in the pixel is DA. We note that:

- Terminal occurrences within the pixel are independent of each other, and are spatially uniform within the pixel. In other words, a terminal is just as likely to be located at one point within the pixel as any other point within the pixel.
- The probability that two or more terminals are located at *exactly* the same point within a pixel is zero. This is simply because there are an infinite number of locations within the pixel.

These imply that terminal occurrence is a spatial Poisson process within the pixel. Therefore the total number of terminals in the pixel satisfies the Poisson distribution:

$$P(k\ \text{terminals}) = (DA)^k\, e^{-DA}\ /\ k! \qquad \textbf{(174)}$$

We choose the number of terminals to assign to the pixel by drawing a number from this Poisson distribution. Doing this at each pixel ensures our terminal distribution is unbiased. Since the sum of many Poisson distributions is also a Poisson distribution, the total number of terminals in the snapshot will also be Poisson distributed.

One may note that if the average number of terminals at a pixel is small ($DA \ll 1$), then working to first order in DA ,

$$\begin{aligned} P(0\ \text{terminal}) &\approx (1 - DA), \\ P(1\ \text{terminal}) &\approx DA. \end{aligned} \qquad \textbf{(175)}$$

So one is effectively making a binary decision about whether a terminal should be placed at the pixel. After creating the random terminal distribution, the terminals are randomly sequenced. This determines the order in which they will be considered during the power iterations.

3.2 Random Speed Distribution

Each randomly scattered terminal in a simulation is given a random speed according to its terminal type and the clutter type in which it resides. For each combination of terminal type and clutter type, the user specifies the following parameters that determine the speed distribution. These are:

μ_{speed}	Mean speed
σ_{speed}	Standard deviation of the speed distribution
$s_{\min}$	Minimum speed
$s_{\max}$	Maximum speed

A random speed is then given by

$$s = \min\left(s_{\max}, \max(\, s_{\min}, \mu_{\text{speed}} + \sigma_{\text{speed}} X\right) \quad \textbf{(176)}$$

where X is a random number drawn from a normal distribution of zero mean and unit variance.

Terminals are randomly assigned as being indoor or outdoor, according to their terminal type and the clutter type in which they reside. Indoor terminals are all given a speed of zero.

When defining a bearer, the user specifies how speed affects the SINR requirement for that bearer. The user enters values at speeds of (in SI units) 3 km/h, 50 km/h, 120 km/h. Values at other speeds are obtained by linear interpolation. Values are not extrapolated to speeds higher than 120 km/h or lower than 3 km/h, which explains the labels (0-3 km/h & >= 120km/h). Therefore stationary terminals will always use the values corresponding to 0-3km/h, and there is no difference between a stationary terminal and one travelling at 3 km/h. The output arrays for the simulation are available at 3 different speeds (0-3 km/h, 50 km/h, 120 km/h) so the user can more clearly see how coverage changes with speed.

3.3 Power Control Modelling

Power control in a real network

In a real network, link powers are modified by *stepping* up or down by a power step size, so the set of possible link TX powers is discrete. A step size of 0 dB is meaningless since powers could never change. Power control is dynamic and imperfect. Hence served terminals will sometimes underachieve SINR requirements and sometimes overachieve them.

Power control in a snapshot

Link powers in a snapshot are modified but *not* by stepping up or down. It is computationally more efficient to calculate a required link power and set it directly, rather than trying to achieve the power via several steps up or down. Therefore there is no reason to restrict link TX powers to a discrete set.

3.4 Power Iterations

The main task in a snapshot is to assign a set of link powers satisfying the SINR requirements of the randomly spread terminals. Before commencing the power iterations, the system is placed in the state of an unloaded network by setting all link powers to zero, and making all resources available at the cells. The link powers in the system are then calculated iteratively by repeatedly cycling through the list of randomly spread terminals and applying the following logic to each terminal.

- If the terminal is already ‘connected’, then ‘disconnect’ it as follows:
  - Zero the UL & DL powers for the terminal.
  - Zero the cell resources used by the terminal.

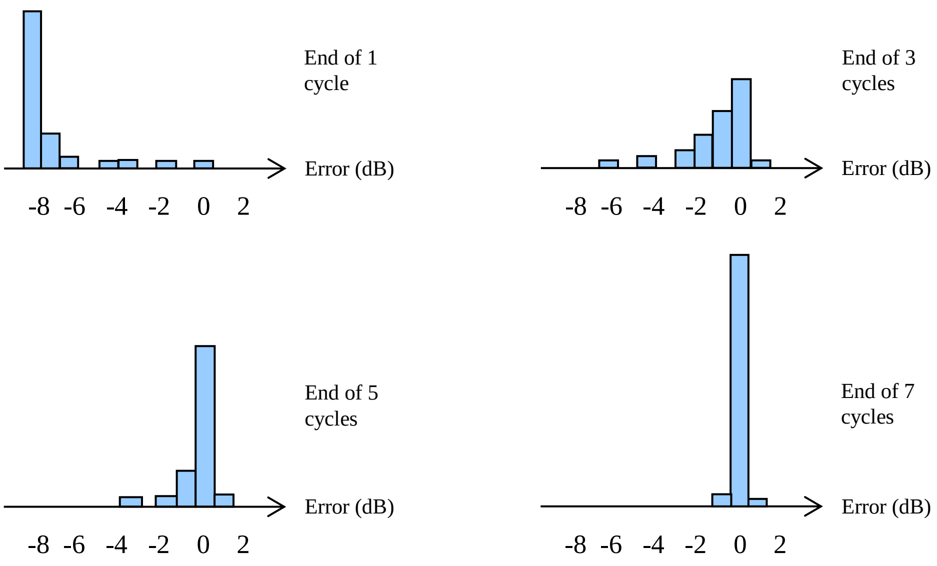
  - Recalculate the UL interference on all cells (because the UL power for the terminal has been zeroed).
  - Recalculate the total DL power on all cells (because the DL powers for the terminal have been zeroed).
  - Recalculate resources available on all cells (because the terminal has released resources).

- Try and 'connect' the terminal to the network in the most favourable way possible. Note that this may be different to the way it was previously 'connected'. For example, it may be preferable to use a different carrier if interference has increased since the last time the terminal was evaluated. The procedure for finding the most favourable method of connection is described in the section on *Connection Evaluation*.

- If a connection is possible, then 'connect' the terminal as follows:
  - Set the UL and DL powers for the terminal.
  - Set the cell resources used by the terminal.
  - Recalculate the UL interference on all cells (because the UL power for the terminal has been set).
  - Recalculate the total DL power on all cells (because the DL powers for the terminal have been set).
  - Recalculate resources available on all cells (because the terminal has consumed resources).

Several cycles through the list of terminals must be performed before a stable set of link powers emerge. The following diagram illustrates how a snapshot converges with successive cycles through the terminal list. The histograms show how 'connected' terminals underachieve their SINR requirements.

After the first cycle through the terminal list, the majority of 'connected' terminals underachieve their SINR requirements. This is because terminals in the first cycle see no interference and so have their link powers set to low values. Successive cycles through the terminal list produce increasingly accurate pictures of network interference. After a few cycles, practically all the 'connected' terminals have link powers that achieve the SINR requirements, and the system interference no longer changes significantly. The power iterations have converged to produce a plausible picture of served and failed terminals in the network.



3.5 CONVERGENCE TEST

A good practical measure of convergence is to examine how the interference changes between cycles. This is considerably faster than measuring the distribution of achieved $SINR$ values described above.

ASSET now uses a much stronger convergence criterion for simulation snapshots, since both the UL and DL are checked. The user only needs to enter a single parameter 'Max Power Change (%)' on the Simulator wizard, which in fact refers to the acceptable power and interference changes between successive iterations. After each cycle through the terminal list, the percentage changes in total UL RX power and total DL TX power are noted. If these *both* fall within the user specified limit for several consecutive iterations, then the snapshot is considered to be converged. So the percentage changes in UL and DL noise must not only become small but must remain small also.

3.6 GATHERING OF RESULTS

The final stage of a snapshot involves gathering results. The information gathered includes cell information (e.g. resource usage, throughput, data rates, DL Power consumption, UL Interference levels and etc.) and the states of 'connected' terminals, and the reasons for failure of terminals which failed to be served.

4 CONNECTION EVALUATION IN A SNAPSHOT

4.1 CONNECTION SCENARIO PRIORITISATION

A *connection scenario* describes how a terminal ‘connects’ to the network and consists of the following set of parameters:

- The carrier used for connection
- The cell used for connection
- The DL bearer used for connection
- The DL transmission mode used for connection
- The DL data rate of the connection (this is given by the DL bearer and DL transmission mode)
- The UL bearer used for connection
- The UL transmission mode used for connection
- The UL data rate of the connection (this is given by the UL bearer and UL transmission mode)

Typically, several connection scenarios are available to each terminal. Our snapshot attempts to connect the randomly spread terminals to the network in the most favourable way possible, so some logic is required for ranking the different scenarios that each terminal may use.

The rules for ranking scenarios during connection evaluation are (in order of decreasing importance):

- Prefer carriers with higher priorities to carriers with lower priorities
- Prefer cells with higher RSRP levels to cells with lower RSRP levels
- Prefer DL scenarios as described in 4.1.1 Bearer Selection Method
- Prefer UL scenarios as described in 4.1.1 Bearer Selection Method

The connection scenarios for each terminal are evaluated in turn (from most to least favoured) until one that permits a network connection is found. The scenario employed by a terminal may change each time it is evaluated in the power iterations, and this flexibility provides us with *link adaptation*.

4.1.1 Bearer Selection Method

The available Bearer Selection Methods are:

- Peak Data Rate:
    - Prefer scenarios (bearer and transmission mode combinations) achieving higher Peak Data Rates
    - If Peak Data Rates are the same, then the prefer scenarios with higher priority transmission modes

- Effective Data Rate:
    - Prefer scenarios (bearer and transmission mode combinations) achieving higher Effective Data Rates
    - This method accounts for the SINR to Error Rate mapping of the bearer: $EffectiveDateRate = PeakDataRate\ (1 - ErrorRate)$
    - If Effective Data Rates are the same, then the prefer scenarios with higher priority transmission modes

- Bearer Index: Prefer bearers with higher index (sorted on top) in the Service definition.
    - For the preferred bearer, prefer scenarios with higher priority transmission modes.

The transmission modes in order of decreasing priority are:

- SU-MIMO Multiplexing
- MU-MIMO
- SU-MIMO Diversity
- Single antenna

4.2 FAILURE REASONS

A connection scenario can fail for one or more of the following reasons:

- **DL RSRP**
  This means that RSRP requirement specified on the terminal type is not satisfied.

- **DL RSRQ**
  This means that RSRQ requirement specified on the terminal type is not satisfied.

- **DL BCH/SCH SINR**
  This means that BCH/SCH SINR requirement specified on the terminal type is not satisfied.

- **UL SINR**
  This means the terminal cannot meet the SINR requirement of the UL bearer, even if the terminal transmits at maximum power.

- **DL SINR**
  This means the cell cannot meet the SINR requirement of the DL bearer.

- **DL Capacity**
  This means the cell has insufficient DL available resources (RBs) to serve the DL bearer.

- **UL Capacity**
  This means the cell has insufficient UL available resources (RBs) to serve the UL bearer.

- **User Limit**
  This means the number of served users on the cell has reached the limit specified by the *# Scheduled Users* cell parameter.

- **No Valid Connection Scenarios**
  This failure reason deals with wrong/conflicting network setup which can result in terminals not being served, e.g. modulation scheme on the cells not supported by the terminal, carriers used by cells are not supported by the service, etc.

- **No Pathloss Data**
  This means that no pathloss data is available for the terminal's location.

If all of the connection scenarios available to a terminal fail to produce a connection, then the terminal is classified as a failure. Note that each scenario in the list can fail for multiple reasons. Also, different scenarios in the list can fail for different sets of reasons. ASSET only records the failure reasons of the top scenario, as in most cases this provides the most useful information as to why a terminal fails. The breakdown of all failure reasons except for '*No Valid Connection Scenarios*' and '*No Pathloss Data*' are logged in respective failure reports.

5 OUTPUT ARRAYS AND REPORTS

5.1 ARRAY DEPENDENCIES

All arrays are produced on a per carrier basis. Most arrays have a dependency on terminal-type because body loss and terminal antenna gain are always included in the linkloss. Many arrays depend on whether the terminal is taken to be indoor or outdoor. Indoor arrays use the in-building parameters for the clutter type at each location (i.e. indoor loss and indoor shadow-fading standard deviation). Indoor terminals are always taken to be slow moving.

Coverage arrays can be drawn even if no snapshots have been run, but the user should note that the arrays then refer to coverage in an *unloaded* system. To obtain coverage arrays for a *loaded* system the user must run some snapshots or define the loads manually. Remember that the key purpose of running snapshots is to provide measures of system load. Arrays for *coverage* tend to have a weak dependence on the number of snapshots run, and the arrays change little after a relatively small number of snapshots have been performed (10s of snapshots in most cases). This is because only a small number of snapshots are needed to get an idea of the 'Mean UL Interference Level (dB)' and 'Downlink Load (%)' on each cell.

The following table lists the types of array that are available in the Simulator, and shows some of their dependencies. The following array dependencies: 'Carrier', 'Terminal', 'Service', 'Velocity' and 'Indoor' indicate that there are per Carrier, per Terminal, per Service, per Velocity and per Indoor instances of the array.

- 'Fading' means the array depends on the standard deviation of shadow fading for the clutter type.

- 'Reliability level' means the array depends on the coverage reliability threshold in the array settings dialog. The user can change this parameter and then redraw the array without running any more snapshots.

- 'Load Levels' means the results of the array are dependent on the load levels defined in the Site Database.

- 'Snapshots': '*P*' means that the presence of the array depends on whether snapshots have been run or not. The results and accuracy of the array are dependent on the number of snapshots done.
  '*X*' means that the results and accuracy of the array are dependent on the number of snapshots done.
- 'Other Tech' means that the presence of the array is dependent on the inclusion of other technology types in the Simulation. Other technology types can be GSM, UMTS and Wi-Fi.

Cell Load Levels (Wizard Step 2)

- If you chose to use cell load levels specified in the database, the arrays are now available for analysis using the Map View.

- If you chose to calculate the cell load levels by running snapshots, you now have a simulation in memory that represents an "unloaded" network, although some arrays are already available for analysis at this stage. At this stage the network is "unloaded" with respect to its own technology type, but still considers any inter-technology DL/UL Noise Rise values that have been set in the Site Database. You can eliminate the effect of inter-technology DL/UL Noise Rise by deselecting the 'Allow Inter-technology Interference' option on the second step of the Simulator wizard. The Simulation Control Panel dialog box appears, and you are now ready to run snapshots to create a simulation of a "loaded" network.

C=**C**arrier **T**=**T**erminal **S**=**S**ervice **V**=Speed/**V**elocity **I**=**I**ndoor
F=**F**ading **R**=**R**eliability level **L**=**L**oad levels **n**=**Sn**apshots **O**=Other Tech
M=MBSFN Area

	C	T	S	V	I	F	R	L	n	O	M
Linkloss Arrays											
DL Loss	X	X			X						
Nth DL Loss	X	X			X						
Line of Sight	X	X			X						
Downlink Reference Signal Coverage Arrays											
Best Server by RSRP	X	X			X						
Nth Best Server by RSRP	X	X			X						
Best RSRP	X	X			X						
Nth Best RSRP	X	X			X						
Nth Best RSRP adjusted by CRE	X	X			X						
CRE Delta	X	X			X						
RSRP Coverage Probability	X	X			X	X					
RSRP Coverage OK	X	X			X	X	X				
Number of RSRP OK	X	X			X	X	X				
Cell Interferers	X	X			X						
Best RSRQ	X	X			X			X	X		
Nth Best RSRQ	X	X			X			X	X		
RSRQ Coverage Probability	X	X			X	X		X	X		
RSRQ Coverage OK	X	X			X	X	X	X	X		
Number of RSRQ OK	X	X			X	X	X	X	X		
DLRS SNR	X	X			X						
DLRS SINR	X	X			X			X	X		
Downlink Noise Array											
RSSI	X	X			X			X	X		
Uplink Coverage Arrays											
Cell for Achievable UL Bearer	X	X	X	X	X	X	X	X	X		
Achievable UL Bearer	X	X	X	X	X	X	X	X	X		
UL Traffic/Ctrl SINR (Power Controlled)	X	X	X	X	X	X	X	X	X		
UL Traffic/Ctrl SINR Margin	X	X	X	X	X	X	X	X	X		
UL Req TX Power	X	X	X	X	X	X	X	X	X		
UL Transmission Mode	X	X	X	X	X	X	X	X	X		
UL MIMO Order	X	X	X	X	X	X	X	X	X		
UL RBs Required for Coverage	X	X	X	X	X	X	X	X	X		
UL TTI Bundling Gain	X	X	X	X	X	X	X	X	X		
Downlink Coverage Arrays											
Cell for Achievable DL Bearer	X	X	X	X	X	X	X	X	X		
Achievable DL Bearer	X	X	X	X	X	X	X	X	X		
DL Traffic/Ctrl SINR	X	X			X			X	X		
DL Traffic SINR	X	X			X			X	X		
DL Ctrl SINR	X	X			X			X	X		
DL BCH/SCH SINR	X	X			X						
DL Transmission Mode	X	X	X	X	X	X	X	X	X		
DL MIMO Order	X	X	X	X	X	X	X	X	X		
DL TTI Bundling Gain	X	X	X	X	X	X	X	X	X		
Downlink Throughput and Data Rate Arrays											
DL Data Rate(Application) (kbps)	X	X	X	X	X	X	X	X	X		
DL Data Rate(Effective) (kbps)	X	X	X	X	X	X	X	X	X		
DL Data Rate(Peak) (kbps)	X	X	X	X	X	X	X	X	X		
DL Achievable Throughput (Application) (kbps)	X	X	X	X	X	X	X	X	X		
DL Achievable Throughput (Effective) (kbps)	X	X	X	X	X	X	X	X	X		
DL Achievable Throughput (Peak) (kbps)	X	X	X	X	X	X	X	X	X		
DL Cell Throughput (Application) (kbps)	X	X			X				P		
DL Cell Throughput (Effective) (kbps)	X	X			X				P		
DL Cell Throughput (Peak) (kbps)	X	X			X				P		
DL Multi-User Rate Gain	X	X	X	X	X	X	X		P		
Uplink Throughput and Data Rate Arrays											
UL Data Rate(Application) (kbps)	X	X	X	X	X	X	X	X	X		
UL Data Rate(Effective) (kbps)	X	X	X	X	X	X	X	X	X		
UL Data Rate(Peak) (kbps)	X	X	X	X	X	X	X	X	X		
UL Achievable Throughput (Application) (kbps)	X	X	X	X	X	X	X	X	X		
UL Achievable Throughput (Effective) (kbps)	X	X	X	X	X	X	X	X	X		
UL Achievable Throughput (Peak) (kbps)	X	X	X	X	X	X	X	X	X		
UL Cell Throughput (Application) (kbps)	X	X			X				P		
UL Cell Throughput (Effective) (kbps)	X	X			X				P		
UL Cell Throughput (Peak) (kbps)	X	X			X				P		
UL Multi-User Rate Gain	X	X	X	X	X	X	X		P		
UL RBs Used (Time-Average)	X	X	X	X	X	X	X	X	X		

	C	T	S	V	I	F	R	L	n	O	M
Miscellaneous Arrays											
Coverage Balance	X	X	X	X	X	X	X	X	X		
All Servers	X	X			X						
Cell Centre/Cell Edge	X	X			X						
DL ABS percentage	X	X			X						
UL ABS percentage	X	X			X						
Carrier Aggregation / Dual Connectivity Arrays											
CA/DC: DC Type		X	X	X	X	X	X	X	X		
CA/DC: Best Cell (MCG)		X	X	X	X	X	X	X	X		
CA/DC: Best Cell (SCG)		X	X	X	X	X	X	X	X		
CA/DC: Number of DL Carriers (MCG)		X	X	X	X	X	X	X	X		
CA/DC: Number of DL Carriers (SCG)		X	X	X	X	X	X	X	X		
CA/DC: Number of UL Carriers (MCG)		X	X	X	X	X	X	X	X		
CA/DC: Number of UL Carriers (SCG)		X	X	X	X	X	X	X	X		
CA/DC: Total DL Throughput (Application) (kbps)		X	X	X	X	X	X	X	X		
CA/DC: Total DL Throughput (Effective) (kbps)		X	X	X	X	X	X	X	X		
CA/DC: Total DL Throughput (Peak) (kbps)		X	X	X	X	X	X	X	X		
CA/DC: Total UL Throughput (Application) (kbps)		X	X	X	X	X	X	X	X		
CA/DC: Total UL Throughput (Effective) (kbps)		X	X	X	X	X	X	X	X		
CA/DC: Total UL Throughput (Peak) (kbps)		X	X	X	X	X	X	X	X		
eMBMS Arrays											
MBSFN Reference Cell	X	X			X						X
MBSFN RSRP	X	X			X						X
MBSFN RSRP Coverage Probability	X	X			X	X	X				X
MBSFN RSRP OK	X	X			X	X	X				X
MBSFN RSRQ	X	X			X			X	X		X
MBSFN RSRQ Coverage Probability	X	X			X	X	X	X	X		X
MBSFN RSRQ OK	X	X			X	X	X	X	X		X
MBSFN RSSI	X	X			X			X	X		X
MBSFN RS SNR	X	X			X						X
MBSFN RS SINR	X	X			X			X	X		X
MBSFN RS SINR Coverage Probability	X	X		X	X	X	X	X	X		X
MBSFN RS SINR OK	X	X		X	X	X	X	X	X		X
MBSFN RS SINR Worst Interference	X	X			X			X	X		X
MBSFN Data BLER	X	X		X	X			X	X		X
MBSFN Data SINR	X	X			X			X	X		X
MBSFN Data SINR Coverage Probability	X	X		X	X	X	X	X	X		X
MBSFN Data SINR OK	X	X		X	X	X	X	X	X		X
MBSFN Data SINR Worst Interferer	X	X			X			X	X		X
MBSFN Ctrl SINR	X	X			X			X	X		X
MBSFN Ctrl SINR Coverage Probability	X	X		X	X	X	X	X	X		X
MBSFN Ctrl SINR OK	X	X		X	X	X	X	X	X		X
MBSFN Ctrl SINR Worst Interferer	X	X			X			X	X		X
MBSFN Service Reference Cell		X	X	X	X	X	X	X	X		
MBSFN Service Area ID		X	X	X	X	X	X	X	X		
MBSFN Service Rate (Application) (kbps)		X	X	X	X	X	X	X	X		
Composite Tech Arrays											
Composite: Best Server		X	X		X	X	X	X	X		
Composite: Tech Type		X	X		X	X	X	X	X	X	
Composite: All Tech Types		X	X		X	X	X	X	X	X	
Composite: Best Carrier / Cell-Layer		X	X		X	X	X	X	X		
Terminal Info Arrays											
Terminal Info: Failure Rate		X							P		
Terminal Info: Failure Reason		X							P		
Terminal Info: Speed (km/h)		X							P		
Terminal Info: Tech Type (Failed)		X							P	X	
Terminal Info: Tech Type (Served)		X							P	X	
Terminal Info: Percentage Served (GSM)		X							P	X	
Terminal Info: Percentage Served (UMTS)		X							P	X	
Terminal Info: Percentage Served (LTE)		X							P	X	
Terminal Info: Percentage Served (Wi-Fi)		X							P	X	
Terminal Info: Percentage Served (No Tech)		X							P	X	
	C	**T**	**S**	**V**	**I**	**F**	**R**	**L**	**n**	**O**	**M**

5.2 Pathloss Arrays

DL Loss & Nth DL Loss
Dependencies: Terminal, Carrier, Indoor

These are the downlink losses of the Best Server and the Nth Best Server by RSRP as calculated by (123). They represent average values and are therefore calculated with fades of 0 dB.

Line of Sight
Dependencies: Terminal, Carrier, Indoor

This is a two-valued array (LOS, non-LOS) for the *Best Server by RSRP*. The indoor instance is non-LOS everywhere. The array is available with Enhanced Macrocell, MYRIAD and Volcano propagation model predictions.

5.3 Downlink Reference Signal Coverage Arrays

These arrays provide information on DLRS levels and coverage probabilities. There are two types of quantity relating to the DLRS, i.e. RSRP and RSRQ. Following arrays are provided for these.

Best Server & Nth Best Server by RSRP
Dependencies: Terminal, Carrier, Indoor

This array reports the cell that provides the highest (and Nth highest) RSRP for the terminal, based on the *Best RSRP* & *Nth Best RSRP* arrays.
If Cell Range Extension cell-specific RSRP offsets have been set in the Site DB, then the determination of the server is based on the *Nth Best RSRP adjusted by CRE* arrays.

Best RSRP & Nth Best RSRP
Dependencies: Terminal, Carrier, Indoor

These are the highest (and Nth highest) RSRP levels as calculated by (164). They represent average values and are therefore calculated with fades of 0 dB.

Nth Best RSRP adjusted by CRE
Dependencies: Terminal, Carrier, Indoor

These are Nth highest RSRP levels as calculated by (164) after accounting for the Cell Range Extension cell-specific RSRP offset. They represent average values and are therefore calculated with fades of 0 dB.

CRE Delta
Dependencies: Terminal, Carrier, Indoor

This is the difference in area coverage due to the Cell Range Extension cell-specific RSRP offset. This difference is the result of the comparison of the Best Server by RSRP with and without the effect of the Cell Range Extension cell-specific RSRP offset.

RSRP Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Fading

This is the probability that the *Best Server by RSRP* satisfies the RSRP requirement specified on the terminal type. This probability depends on the standard deviation of shadow fading for the clutter type at the location. If this standard deviation has been set to zero, then there are only three possible coverage probabilities: 0% if the requirement is not satisfied, 50% if the requirement is satisfied exactly, and 100% if the requirement is exceeded.

RSRP Coverage OK
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability

This is a thresholded version of the *RSRP Coverage Probability* array and has just two values (Yes/No). It has the advantage of being quicker to calculate than the *RSRP Coverage Probability* array. A value of 'Yes' means that the RSRP coverage probability meets the coverage reliability level specified in *Array Settings→ Sim Display Settings*.

Number of RSRP OK
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability

This is the number of covering cells with a satisfactory RSRP. A cell is counted as having a satisfactory RSRP if its RSRP coverage probability meets the coverage reliability level specified in *Array Settings → Sim Display Settings.*

Cell Interferers
Dependencies: Terminal, Carrier, Indoor

This is the number of Cell Interferers. That is the number of cells, excluding the serving cell, providing an RSRP value within *x* dB of the RSRP value of the serving cell or higher than the RSRP value of the serving cell. The *x* dB threshold is relative and specified at the Simulator Wizard.

RSRQ
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the RSRQ value as calculated by (166). It represents an average value and is therefore calculated with fades of 0 dB.

Nth Best RSRQ
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the RSRQ value for the *Nth Best Server by RSRP*. It represents an average value and is therefore calculated with fades of 0 dB.

RSRQ Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Fading, Snapshots/Load levels

This is the probability that the *Best Server by RSRP* satisfies the RSRQ requirement specified on the terminal type. This probability depends on the standard deviation of shadow fading for the clutter type at the location. If this standard deviation has been set to zero, then there are only three possible coverage probabilities: 0% if the requirement is not satisfied, 50% if the requirement is satisfied exactly, and 100% if the requirement is exceeded.

RSRQ Coverage OK
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability, Snapshots/Load levels

This is a thresholded version of the *RSRQ Coverage Probability* array and has just two values (Yes/No). It has the advantage of being quicker to calculate than the *RSRQ Coverage Probability* array. A value of 'Yes' means that the RSRQ coverage probability meets the coverage reliability level specified in *Array Settings → Sim Display Settings*.

Number of RSRQ OK
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability, Snapshots/Load levels

This is the number of covering cells with a satisfactory RSRQ. A cell is counted as having a satisfactory RSRQ if its RSRQ coverage probability meets the coverage reliability level specified in *Array Settings* → *Sim Display Settings.*

DLRS SNR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the DLRS SNR level of the *Best Server by RSRP* as calculated by (167). This does not include the interference (i.e. Best RSRP levels divided by the thermal noise); represents an average value and is therefore calculated with fades of 0 dB.

DLRS SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the DLRS SINR level of the *Best Server by RSRP* as calculated via (168). This includes the Inter-cell interference (i.e. Best RSRP levels divided by the thermal noise plus Inter-cell Interference); represents an average value and is therefore calculated with fades of 0 dB.

5.4 Downlink Noise Arrays

RSSI (Downlink Received Power)
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the is the total received noise contributed by all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise as calculated by (165). This represents average values and is therefore calculated with fades of 0 dB.

5.5 UL Coverage Arrays

Cell for Achievable UL Bearer
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is required for the Achievable UL Bearer array. It is similar to *Best Server by RSRP* array but includes all bearers' dependencies and shows the server which provides the connection for the UL bearer at a given location.

Achievable UL Bearer
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

The purpose of this array is to provide a combined coverage plot for the UL bearers of the service. The array shows the best bearer with acceptable UL coverage, i.e. with *UL coverage probability* meeting the reliability level specified in *Array Settings → Sim Display Settings.* Bearers are ranked based on the Bearer Selection Method as described in section 4.1.

UL Traffic/Ctrl SINR (Power Controlled)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the achieved UL SINR level assuming that the terminal transmits at the power controlled power level, i.e. when the terminal is using the *Achievable UL Bearer*. Uplink is powered controlled and the terminal transmits just at the level required to meet the SINR of the bearer. The achieved SINR is equal to the bearer SINR requirement after all MIMO adjustments.

UL Traffic/Ctrl SINR Margin
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is given by (163) and shows by how much the maximum UL TX power of the terminal exceeds the *UL Req TX power* at a given location.

UL Req TX power
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the required UL TX power of the terminal to serve the achievable UL bearer at a given location as calculated via (159).

UL Transmission Mode
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the achievable UL Advanced Antenna Systems (AAS) mode at a given location. The supported UL transmission modes are 'Single Antenna', 'SU-MIMO Diversity', 'SU-MIMO Multiplexing' and 'MU-MIMO'. This array can be used in conjunction with the *Achievable UL Bearer* array to determine the achievable UL bearer and transmission mode at a given location.

UL MIMO Order
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the number of TX and RX antennas for the *UL Transmission Mode* with the category "MxN" indicating there are M transmit elements and N receive elements. Only the most common values of M and N are reported (i.e. 1,2,4,8). All other cases are grouped together in the category "Other".

UL RBs Required for Coverage
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the maximum required number of UL Resource Blocks, for the highest achievable UL bearer, over which the terminal can transmit (spread its power) without losing coverage of the bearer. The required number of RBs is restricted by the employed carrier bandwidth and the ICIC settings.

UL TTI Bundling Gain
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the UL TTI Bundling gain for the serving *Cell for Achievable UL Bearer*.

5.6 DL Coverage Arrays

Cell for Achievable DL Bearer
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is required for the Achievable DL Bearer array. It is similar to *Best Server by RSRP* array and shows the server which provides the connection for the DL bearer at a given location.

Achievable DL Bearer
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

The purpose of this array is to provide a combined coverage plot for the DL bearers of the service. The array shows the best bearer with acceptable DL coverage, i.e. with *DL coverage probability* meeting the reliability level specified in *Array Settings → Sim Display Settings.* Bearers are ranked based on the Bearer Selection Method as described in section 4.1.

DL Traffic/Ctrl SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the highest PDSCH/PDCCH SINR levels as calculated by (170). This represents an average value and is therefore calculated with fades of 0 dB.

DL Traffic SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the highest PDSCH SINR levels as calculated by (172). This represents an average value and is therefore calculated with fades of 0 dB.

DL Ctrl SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels

This is the highest PDCCH SINR levels as calculated by (171). This represents an average value and is therefore calculated with fades of 0 dB.

DL BCH/SCH SINR
Dependencies: Terminal, Carrier, Indoor

This is the highest PBCH/P-SCH+S-SCH SINR levels as calculated by (169). This represents an average value and is therefore calculated with fades of 0 dB.

DL Transmission Mode
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the achievable DL Advanced Antenna Systems (AAS) mode at a given location. The supported DL transmission modes are 'Single Antenna', 'SU-MIMO Diversity', 'SU-MIMO Multiplexing' and 'MU-MIMO'. This array can be used in conjunction with the *Achievable DL Bearer* array to determine the achievable DL bearer and transmission mode at a given location.

DL MIMO Order
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the number of TX and RX antennas for the *DL Transmission Mode* with the category "MxN" indicating there are M transmit elements and N receive elements. Only the most common values of M and N are reported (i.e. 1,2,4,8). All other cases are grouped together in the category "Other".

DL TTI Bundling Gain
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the DL TTI Bundling gain for the serving *Cell for Achievable DL Bearer*.

5.7 BEAMFORMING GAIN ARRAYS

Beamformer DL SINR Gain
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Snapshots/Load levels

This shows the DL Beamforming SINR gain (which is the same as DL Beamforming Signal Gain) for a terminal that is served by DL beamforming. Assuming that no angular spread values are set in the clutter categories, then a terminal served by adaptive-beamforming will show a single gain value across the cell. A terminal served by switched-beamforming will show stronger beamforming gain in the directions corresponding to the main lobes of the switched-beam patterns.

Beamformer UL SINR Gain
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Snapshots/Load levels

This shows the UL Beamforming SINR gain for a connection that is served by UL beamforming. A terminal served by UL adaptive-beamforming will usually have a higher UL SINR gain due to beamforming when using the *Maximise SINR* method instead of the *Maximise Signal* method. If switched-beamforming is used instead, then the beamforming method has much less of an effect and plots for the two methods will be almost identical, although the *Maximise Signal* method will be faster to evaluate.

5.8 DOWNLINK THROUGHPUT AND DATA RATE ARRAYS

This category of arrays is tiered at Peak, Effective and Application level, and the generic relation between the levels is given by:

$Peak_R$ = BearerRate
$Effective_R$ = $Peak_R$ · (1- ErrorRate)
$Application_R$ = $Effective_R$ / [(1+ ServiceOverheads) · (1+ TTIbundlingOverheads)]

DL Data Rate (Application) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the application layer data rate for the highest achievable DL bearer and the employed SU/MU-MIMO settings. This also takes into account the SINR to Error Rate mapping defined on the DL bearers as well the reduction in data rate due to service overheads.

DL Data Rate (Effective) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the effective data rate for the highest achievable DL bearer and the employed SU/MU-MIMO settings. This also takes into account the SINR to Error Rate mapping defined on the DL bearers but not the service overheads.

DL Data Rate (Peak) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the peak data rate, at physical layer, for the highest achievable DL bearer and the employed SU/MU-MIMO settings without taking into account the SINR to Error Rate mapping defined on the DL bearers and service overheads.

DL Achievable Throughput (Application) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the application throughput that a user can achieve at a location using the highest achievable DL bearer and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the DL bearers and service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Application)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

DL Achievable Throughput (Effective) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the effective throughput that a user can achieve at a location using the highest achievable DL bearer and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the DL bearers but not the service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Effective)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

DL Achievable Throughput (Peak) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the peak throughput, at physical layer, that a user can achieve at a location using the highest achievable DL bearer and the employed SU/MU-MIMO and ICIC settings. The peak throughput is reported without taking into account the SINR to Error Rate mapping defined on the DL bearers and service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Peak)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

DL Cell Throughput (Application) (kbps)
Dependencies: Carrier, Snapshots

This is the application layer DL cell throughput displayed over the *Best Server by RSRP* area. The presence of this array requires the Simulator to run in the snapshot mode as it requires the cell throughput results gathered at the end of snapshots. This array reflects the results from 5.15.1 5.15.1Throughput Reports: LTE - Application DL Throughput Report (kbps).

DL Cell Throughput (Effective) (kbps)
Dependencies: Carrier, Snapshots

This is the effective DL cell throughput displayed over the *Best Server by RSRP* area. The presence of this array requires the Simulator to run in the snapshot mode as it requires the cell throughput results gathered at the end of snapshots. This array reflects the results from 5.15.1Throughput Reports: LTE - Effective DL Throughput Report (kbps).

DL Cell Throughput (Peak) (kbps)
Dependencies: Carrier, Snapshots

This is the peak DL cell throughput, at physical layer, displayed over the *Best Server by RSRP* area. The presence of this array requires the Simulator to run in the snapshot mode as it requires the cell throughput results gathered at the end of snapshots. This array reflects the results from 5.15.1Throughput Reports: LTE - Peak DL Throughput Report (kbps).

DL Multi-User Rate Gain
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots

This is DL Multi User Gain for cells with Proportional Fair scheduler, as calculated by (199).

5.9 UPLINK THROUGHPUT AND DATA RATE ARRAYS

This category of arrays is tiered at Peak, Effective and Application level, and the generic relation between the levels is given by:

$Peak_R$ = BearerRate
$Effective_R$ = $Peak_R$ · (1- ErrorRate)
$Application_R$ = $Effective_R$ / [(1+ ServiceOverheads) · (1+ TTIbundlingOverheads)]

UL Data Rate (Application) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the application layer data rate for the highest achievable UL bearer and the employed SU/MU-MIMO settings. This also takes into account the SINR to Error Rate mapping defined on the UL bearers as well the reduction in data rate due to service overheads.

UL Data Rate (Effective) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the effective data rate for the highest achievable UL bearer and the employed SU/MU-MIMO settings. This also takes into account the SINR to Error Rate mapping defined on the UL bearers but not the service overheads.

UL Data Rate (Peak) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the peak data rate, at physical layer, for the highest achievable UL bearer and the employed SU/MU-MIMO settings without taking into account the SINR to Error Rate mapping defined on the UL bearers and service overheads.

UL Achievable Throughput (Application) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the application throughput that a user can achieve at a location using the highest achievable UL bearer and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the UL bearers and service overheads. The reported value is not limited by the service MBR. The *UL Achievable Throughput (Application)* is achievable over the RBs that have been calculated by the *UL RBs Required for Coverage* array.

UL Achievable Throughput (Effective) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the effective throughput that a user can achieve at a location using the highest achievable UL bearer and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the UL bearers but not the service overheads. The reported value is not limited by the service MBR. The *UL Achievable Throughput (Effective)* is achievable over the RBs that have been calculated by the *UL RBs Required for Coverage* array.

UL Achievable Throughput (Peak) (kbps)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the peak throughput, at physical layer, that a user can achieve at a location using the highest achievable UL bearer and the employed SU/MU-MIMO and ICIC settings. The peak throughput is reported without taking into account the SINR to Error Rate mapping defined on the UL bearers and service overheads. The reported value is not limited by the service MBR. The *UL Achievable Throughput (Peak)* is achievable over the RBs that have been calculated by the *UL RBs Required for Coverage* array.

UL Cell Throughput (Application) (kbps)
Dependencies: Carrier, Snapshots

This is the application layer UL cell throughput displayed over the *Best Server by RSRP* area. The presence of this array requires the Simulator to run in the snapshot mode as it requires the cell throughput results gathered at the end of snapshots. This array reflects the results from 5.15.1Throughput Reports: LTE - Application UL Throughput Report (kbps).

UL Cell Throughput (Effective) (kbps)
Dependencies: Carrier, Snapshots

This is the effective UL cell throughput displayed over the *Best Server by RSRP* area. The presence of this array requires the Simulator to run in the snapshot mode as it requires the cell throughput results gathered at the end of snapshots. This array reflects the results from 5.15.1Throughput Reports: LTE - Effective UL Throughput Report (kbps).

UL Cell Throughput (Peak) (kbps)
Dependencies: Carrier, Snapshots

This is the peak UL cell throughput, at physical layer, displayed over the *Best Server by RSRP* area. The presence of this array requires the Simulator to run in the snapshot mode as it requires the cell throughput results gathered at the end of snapshots. This array reflects the results from 5.15.1Throughput Reports: LTE - Peak UL Throughput Report (kbps).

UL Multi-User Rate Gain
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots

This is UL Multi User Gain for cells with Proportional Fair scheduler, as calculated by (199).

UL RBs Used (Time-Average)
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This shows the time-average number of UL Resource Blocks required by the highest achievable UL bearer in order to achieve the service GBR. In case of SU-MIMO Spatial Multiplexing the value is reduced by the UL SM Rate Gain. The *UL RBs Used (Time-Average)* at a location is always less than or equal to the *UL RBs Required for Coverage*.

5.10 Miscellaneous Arrays

Coverage Balance
Dependencies: Terminal, Carrier, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

The purpose of this array is to provide a composite uplink/downlink coverage plot for a service. The uplink is deemed to have coverage if *any* of the uplink bearers on the service have *UL Coverage Probability* meeting the coverage reliability level specified in *Array Settings → Sim Display Settings.* Similarly, the downlink is deemed to have coverage if *any* of the downlink bearers on the service have *DL Coverage Probability* meeting the coverage reliability level specified in *Array Settings → Sim Display Settings.*

All Servers
Dependencies: Terminal, Carrier, Indoor

This is not a true array, since it is sensitive to the location of mouse cursor. It displays information about which cells are 'covering' each pixel based on the 'All Servers' display properties (*either RSRP or RSRQ*). A set of lines is drawn between all possible serving cells to the simulation pixel where the mouse cursor is located. For pixels with more than one covering cell, the line thickness increases proportionally.

Cell Centre/Cell Edge
Dependencies: Terminal, Carrier, Indoor

This arrays shows the division of the *Best Server by RSRP* area into 'Cell Centre' and 'Cell Edge' based on the selected '*Cell Edge Threshold*' setting on the '*LTE Params →Thresholds*' tab. It has only two values, '*Cell Centre*' and '*Cell Edge*' depicting the classification of service area.

The available '*Cell Edge Threshold*' settings are '*RSRP (dBm)*' and '*Relative RSRP (dB)*'. The latter translates to the difference between the RSRP levels of the best and 2nd best server by RSRP at a given location.

DL ABS percentage
Dependencies: Terminal, Carrier, Indoor

This is the DL percentage of Almost Blank Subframes as specified for each cell for Cell Centre and Cell Edge in LTE Params in the Site Database, for the Best Server by RSRP.

UL ABS percentage
Dependencies: Terminal, Carrier, Indoor

This is the UL percentage of Almost Blank Subframes as specified for each cell for Cell Centre and Cell Edge in LTE Params in the Site Database, for the Best Server by RSRP.

5.11 Carrier Aggregation/Dual Connectivity Arrays

When a terminal is using Dual Connectivity (DC) it has connections to cells belonging to two groups, the Master Cell Group (MCG) and the Secondary Cell Group (SCG). The cells within each group belong to the same MU-Node. Carrier Aggregation (CA) occurs when more than one carrier is used within a cell group. The following set of arrays handle both multi-carrier (i.e. DC and CA) and single-carrier connections.

CA/DC: DC Type
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

There are 6 categories with the following meaning.

LTE-DC	Dual-connectivity.	MCG is LTE.	SCG is LTE.
EN-DC	Dual-connectivity.	MCG is LTE.	SCG is NR.
NE-DC	Dual-connectivity.	MCG is NR.	SCG is LTE.
NR-DC	Dual-connectivity.	MCG is NR.	SCG is NR
LTE (No DC)	No dual-connectivity.	MCG is LTE.	No SCG.
NR (No DC)	No dual-connectivity.	MCG is NR.	No SCG.

CA/DC: Best Cell (MCG)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the best cell in the MCG with the cells ranked by the carrier priorities specified on the service type and by DL RSRP. If CA is used in the MCG then the reported cell will be the *primary cell* and have a carrier in the set of allowed P-Cell carriers specified on the terminal type.
Note that this plot reports a value even if there is no dual-connectivity (i.e. when all connections are of the same technology and on the same node), or even for single-carrier situations in which case the plot simply reports the cell used for connection.

CA/DC: Best Cell (SCG)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the best cell in the SCG with the cells ranked by the carrier priorities specified on the service type and by DL RSRP. If CA is used in the SCG then the reported cell will be the *primary cell* and have a carrier in the set of allowed P-Cell carriers specified on the terminal type.
Note that this plot will not report a value if there is no dual-connectivity.

CA/DC: Number of DL Carriers (MCG)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the number of carriers/cells used for the downlink in the MCG. Each carrier must be supported by the terminal and the service, and there must be an achievable DL bearer for the carrier.
If the reported value is greater than one then this indicates that DL CA is being used in the MCG. When CA is being used, the carrier of the primary cell will be in the set of allowed P-Cell carriers specified on the terminal type, and the remaining (secondary) cells in the MCG will have carriers in the set of allowed S-Cell carriers specified on the terminal type.

CA/DC: Number of DL Carriers (SCG)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the number of carriers/cells used for the downlink in the SCG. Each carrier must be supported by the terminal and the service, and there must be an achievable DL bearer for the carrier.
If the reported value is greater than one then this indicates that DL CA is being used in the SCG. When CA is being used, the carrier of the primary cell will be in the set of allowed P-Cell carriers specified

on the terminal type, and the remaining (secondary) cells in the SCG will have carriers in the set of allowed S-Cell carriers specified on the terminal type.
Note that this plot will report a value of zero if there is no dual-connectivity.

CA/DC: Number of UL Carriers (MCG)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the number of carriers/cells used for the uplink in the MCG. Each carrier must be supported by the terminal and the service, and there must be an achievable UL bearer for the carrier.
If the reported value is greater than one then this indicates that UL CA is being used in the MCG. When CA is being used, the carrier of the primary cell will be in the set of allowed P-Cell carriers specified on the terminal type, and the remaining (secondary) cells in the MCG will have carriers in the set of allowed S-Cell carriers specified on the terminal type.
The total power transmitted over all carriers in the UL must not exceed the power limits specified on the terminal.

CA/DC: Number of UL Carriers (SCG)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the number of carriers/cells used for the uplink in the SCG. Each carrier must be supported by the terminal and the service, and there must be an achievable UL bearer for the carrier.
If the reported value is greater than one then this indicates that UL CA is being used in the SCG. When CA is being used, the carrier of the primary cell will be in the set of allowed P-Cell carriers specified on the terminal type, and the remaining (secondary) cells in the SCG will have carriers in the set of allowed S-Cell carriers specified on the terminal type.
The total power transmitted over all carriers in the UL must not exceed the power limits specified on the terminal.
Note that this plot will report a value of zero if there is no dual-connectivity.

CA/DC Throughput Arrays

The following throughput arrays are tiered at Peak, Effective and Application level, and the generic relation between the levels is given by:

$\text{Peak}_R = \text{BearerRate}$
$\text{Effective}_R = \text{Peak}_R \cdot (1 - \text{ErrorRate})$
$\text{Application}_R = \text{Effective}_R / [\, (1 + \text{ServiceOverheads}) \cdot (1 + \text{TTIbundlingOverheads}) \,]$

CA/DC: Total DL Throughput (Application) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the application throughput that a user can achieve at a location using the best achievable set of DL bearers and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the DL bearers and service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Application)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

CA/DC: Total DL Throughput (Effective) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the effective throughput that a user can achieve at a location using the best achievable set of DL bearers and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the DL bearers but not the service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Effective)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

CA/DC: Total DL Throughput (Peak) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the peak throughput, at physical layer, that a user can achieve at a location using the best achievable set of DL bearers and the employed SU/MU-MIMO and ICIC settings. The peak throughput is reported without taking into account the SINR to Error Rate mapping defined on the DL bearers and service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Peak)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

CA/DC: Total UL Throughput (Application) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the application throughput that a user can achieve at a location using the best achievable set of UL bearers and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the UL bearers and service overheads. The reported value is not limited by the service MBR. *The UL Achievable Throughput (Application)* is achievable over the set of RBs occupied by the best achievable set of UL bearers.

CA/DC: Total UL Throughput (Effective) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the effective throughput that a user can achieve at a location using the best achievable set of UL bearers and the employed SU/MU-MIMO and ICIC settings. This also takes into account the SINR to Error Rate mapping defined on the UL bearers but not the service overheads. The reported value is not limited by the service MBR. The *UL Achievable Throughput (Effective)* is achievable over the set of RBs occupied by the best achievable set of UL bearers.

CA/DC: Total UL Throughput (Peak) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the peak throughput, at physical layer, that a user can achieve at a location using the best achievable set of DL bearers and the employed SU/MU-MIMO and ICIC settings. The peak throughput is reported without taking into account the SINR to Error Rate mapping defined on the DL bearers and service overheads. The reported value is not limited by the service MBR. The *DL Achievable Throughput (Peak)* is achievable over the available RBs in the present ICIC bandwidth partition (cell centre or cell edge).

5.12 eMBMS Arrays

These arrays are present if cells, terminals and services have been configured for eMBMS operation.

MBSFN Reference Cell
Dependencies: Terminal, Carrier, Indoor, MBSFN Area

This array reports the nearest covering eMBMS-enabled cell for the terminal.
If the terminal name contains "_STRONGEST" then this array reports the eMBMS-enabled cell that provides the strongest (highest) RSRP for the terminal.

MBSFN RSRP
Dependencies: Terminal, Carrier, Indoor, MBSFN Area

This is the MBSFN RSRP level, for the *MBSFN Reference Cell*, as calculated by (54). It represents average values and is therefore calculated with fades of 0 dB.

MBSFN RSRP Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability, MBSFN Area

This is the probability that the *MBSFN Reference Cell* satisfies the eMBMS RSRP requirement specified on the terminal type. This probability depends on the standard deviation of shadow fading for the clutter type at the location.

MBSFN RSRP OK
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability, MBSFN Area

This is a thresholded version of the *RSRP Coverage Probability* array and has just two values (Yes/No). A value of 'Yes' means that the RSRP coverage probability meets the coverage reliability level specified in *Array Settings→Sim Display Settings*. See section 2.14 on MBSFN calculations.

MBSFN RSRQ
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This is the MBSFN RSRQ value, for the *MBSFN Reference Cell*, as calculated by (55). It represents an average value and is therefore calculated with fades of 0 dB.

MBSFN RSRQ Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is the probability that the *MBSFN Reference Cell* satisfies the eMBMS RSRQ requirement specified on the terminal type. This probability depends on the standard deviation of shadow fading for the clutter type at the location.

MBSFN RSRQ OK
Dependencies: Terminal, Carrier, Indoor, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is a thresholded version of the *MBSFN RSRQ Coverage Probability* array and has just two values (Yes/No). A value of 'Yes' means that the RSRQ coverage probability meets the coverage reliability level specified in *Array Settings→Sim Display Settings*. See section 2.14 on MBSFN calculations.

MBSFN RSSI
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This is the is the total received noise contributed by all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise as calculated by (50). This represents average values and is therefore calculated with fades of 0 dB.

MBSFN RS SNR
Dependencies: Terminal, Carrier, Indoor, MBSFN Area

This is the MBSFN RS SNR level of the *MBSFN Reference Cell*. This does not include the interference (i.e. MBSFN RSRP levels divided by the thermal noise); represents an average value and is therefore calculated with fades of 0 dB.

MBSFN RS SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This is the MBSFN RS SINR level of the *MBSFN Reference Cell* as calculated by (56). It represents an average value and is therefore calculated with fades of 0 dB.

MBSFN RS SINR Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Speed, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is the probability that the *MBSFN Reference Cell* satisfies the eMBMS RS SINR requirement specified on the terminal type. This probability depends on the standard deviation of shadow fading for the clutter type at the location. See section on MBSFN calculations.

MBSFN RS SINR OK
Dependencies: Terminal, Carrier, Indoor, Speed, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is a thresholded version of the *MBSFN RS SINR Coverage Probability* array and has just two values (Yes/No). A value of 'Yes' means that the RSRP coverage probability meets the coverage reliability level specified in *Array Settings→ Sim Display Settings*.

MBSFN RS SINR Worst Interferer
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This array reports the worst interfering LTE cell that is the cell causing the greatest deterioration in the *MBSFN RS SINR* array.

MBSFN Data BLER
Dependencies: Terminal, Carrier, Indoor, Speed, Snapshots/Load levels, MBSFN Area

This is the Error Rate of the *MBSFN Reference Cell* as calculated by the SINR to Error Rate Mapping. The SINR is input from *MBSFN Data SINR* array and the Error Rate Mapping is specified on the eMBMBS Traffic bearer of the serving MBSFN Area. It represents an average value and is therefore calculated with fades of 0 dB.

MBSFN Data SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This is the MBSFN Data SINR level of the *MBSFN Reference Cell* as calculated by (56). It represents an average value and is therefore calculated with fades of 0 dB.

MBSFN Data SINR Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Speed, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is the probability that the *MBSFN Reference Cell* satisfies the SINR requirement specified on the eMBMBS Traffic bearer of the serving MBSFN Area. This probability depends on the standard deviation of shadow fading for the clutter type at the location. See section 2.14 on MBSFN calculations.

MBSFN Data SINR OK
Dependencies: Terminal, Carrier, Indoor, Speed, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is a thresholded version of the *MBSFN Data SINR Coverage Probability* array and has just two values (Yes/No). A value of 'Yes' means that the RSRP coverage probability meets the coverage reliability level specified in *Array Settings→Sim Display Settings*.

MBSFN Data SINR Worst Interferer
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This array reports the worst interfering LTE cell that is the cell causing the greatest deterioration in the *MBSFN Data SINR* array.

MBSFN Ctrl SINR
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This is the MBSFN Ctrl SINR level of the *MBSFN Reference Cell* as calculated by (56). It represents an average value and is therefore calculated with fades of 0 dB.

MBSFN Ctrl SINR Coverage Probability
Dependencies: Terminal, Carrier, Indoor, Speed, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is the probability that the *MBSFN Reference Cell* satisfies the SINR requirement specified on the eMBMS Control (MCCH) bearer of the serving MBSFN Area. This probability depends on the standard deviation of shadow fading for the clutter type at the location. See section 2.14 on MBSFN calculations.

MBSFN Ctrl SINR OK
Dependencies: Terminal, Carrier, Indoor, Speed, Fading, Reliability, Snapshots/Load levels, MBSFN Area

This is a thresholded version of the *MBSFN Ctrl SINR Coverage Probability* array and has just two values (Yes/No). A value of 'Yes' means that the RSRP coverage probability meets the coverage reliability level specified in *Array Settings→Sim Display Settings*.

MBSFN Ctrl SINR Worst Interferer
Dependencies: Terminal, Carrier, Indoor, Snapshots/Load levels, MBSFN Area

This array reports the worst interfering LTE cell that is the cell causing the greatest deterioration in the *MBSFN Ctrl SINR* array.

MBSFN Service Reference Cell
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is *MBSFN Reference Cell* over which the Service is achieved. The terminal requirements must be met: RSRP, RSRQ, BCH/SCH SINR, eMBMS SINR, eMBMS, RSRQ and eMBMS RS SINR. The achieved *MBSFN Service Rate (Application)* must be greater than the Service Rate requirement.

MBSFN Service Area ID
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is *MBSFN Area ID* over which the Service is achieved. The terminal requirements must be met: RSRP, RSRQ, BCH/SCH SINR, eMBMS SINR, eMBMS, RSRQ and eMBMS RS SINR. The achieved *MBSFN Service Rate (Application)* must be greater than the Service Rate requirement.

MBSFN Service Rate (Application) (kbps)
Dependencies: Terminal, Service, Indoor, Speed, Fading, Reliability, Snapshots/Load levels

This is the MBSFN Service Rate at Application layer that a user can achieve using the highest achievable eMBMS Traffic bearer. This also takes into account the SINR to Error Rate mapping defined on the eMBMS Traffic bearer and the service overheads. The reported value is not limited by the service rate requirement.

5.13 COMPOSITE TECH ARRAYS

Composite Tech Arrays can account for GSM, UMTS, LTE and Wi-Fi cells collectively.

Composite: Best Server
Dependencies: Terminal, Indoor, Service, Fading, Reliability, Snapshots/Load levels

This is the serving cell identity. Cell ranking is primarily based on the carrier/cell layer priorities which are specified off the Service. Secondarily, cells of a specific technology type are ordered by Signal Strength (GSM: RSS, UMTS: RSCP, LTE: RSRP, Wi-Fi: DL RSS). The terminal's requirements must be met for the respective technology (GSM: Receiver RSS Sensitivity, UMTS: Required RSCP, Ec/Io and Pilot SIR, LTE: Required RSRP, RSRQ and BCH/SCH SINR, Wi-Fi: Required Signal Strength). The array has a dependency on Cell Load Levels, due to the interference-related terminal requirements. The display thresholds are set for each technology type individually in *Array Settings→ Sim Display Settings*.

Composite: Tech Type
Dependencies: Terminal, Indoor, Service, Fading, Reliability, Snapshots/Load levels, Other Tech

This is the technology type of the serving cell as determined in the *Composite: Best Server* array.

Composite: All Tech Types
Dependencies: Terminal, Indoor, Service, Fading, Reliability, Snapshots/Load levels, Other Tech

This is the combination (not ordered list) of achieved technology types. It is a superset of the *Composite: Tech Type* array.

Composite: Best Carrier / Cell-Layer
Dependencies: Terminal, Indoor, Service, Fading, Reliability, Snapshots/Load levels

This is the Carrier in case of UMTS, LTE and Wi-Fi, or Cell-Layer in case of GSM of the serving cell as determined in *Composite: Best Server* array.

5.14 Terminal Info Arrays

Terminal Info: Failure Rate
Dependencies: Terminal, Snapshots

The failure rate is the proportion of attempted terminals at a pixel that failed to make a connection. It is calculated as a percentage as follows:

Failure Rate (%) = 100 * (Failed Terminals) / (Attempted Terminals)

The accuracy of the result at a pixel is clearly limited by the number of attempts made at the pixel. For example, if only one attempt has been made, the result will either be 0% or 100%. So the *Failure Rate* array gives a rough visualisation of the problem areas of the network.

Terminal Info: Failure Reason
Dependencies: Terminal, Snapshots

This plot shows failures and successes in a single plot. The value shown at a pixel is determined by the last terminal that was attempted there, regardless of the snapshot in which it was attempted. So if the last terminal that was attempted at a pixel succeeded, then the pixel will be labelled a success, regardless of how many terminals may have failed there in other snapshots. Likewise, if the last terminal at a pixel failed, then the pixel will be labelled as a failure, regardless of how many terminals succeeded there in other snapshots. Therefore locations that are more likely to serve terminals in a snapshot rather than fail them are more likely to be labelled as successes than failures.

A terminal can fail for multiple reasons. When this occurs, only a single reason is reported when writing a value at the pixel. This is achieved by sensibly ranking the failure reasons for the terminal and using the most dominant one. For example, there is no point in indicating a capacity failure for a terminal if it does not have coverage. In other words, coverage failures rank more highly than capacity failures.

The failure reason categories are ranked as follows (most dominant failure reasons first). For clarity, the categories in the legend are shown in the same order.

- Success
- No Covering Cells
- No Valid Scenarios
- DL RSRP
- RSRQ
- DL BCH/SCH SINR
- UL SINR
- DL SINR
- UL Capacity
- DL Capacity
- User Limit

Terminal Info: Speed (km/h)
Dependencies: Terminal, Snapshots

This plot shows the speed of the terminal in the corresponding *Failure Reason* plot. The value shown at a pixel is determined by last terminal that was attempted there, regardless of the snapshot in which it was attempted.

Terminal Info: Tech Type

This category comprises two arrays, the *Terminal Info: Tech Type (Served)* and the *Terminal Info: Tech Type (Failed)*. After a terminal has been evaluated in a snapshot, it will be marked in precisely one of the following ways:

1) As failure due to “No Valid Scenarios / No Covering Cells” in the *Tech Type (Failed)* array.
   It will also appear as a “No Valid Scenarios / No Covering Cells” failure in the *Failure Reason* array of every individual technology.
2) As a success in *Tech Type (Served)* array, showing the tech type used for connection.
   The *Failure Reason* array for that technology will show “Success”.
3) As a failure in the *Tech Type (Failed)* array, showing the tech of the most relevant failure reason.
   The *Failure Reason* array for that technology will show the according failure reason.

Terminal Info: Tech Type (Served)
Dependencies: Terminal, Snapshots, Other Tech

This array shows the serving technology type (GSM, UMTS, LTE or Wi-Fi) where
the *Terminal Info (GSM): Failure Reason* array is reporting Success or
the *Terminal Info (UMTS): Failure Reason* array is reporting Success or
the *Terminal Info (LTE): Failure Reason* array is reporting Success or
the *Terminal Info (Wi-Fi): Failure Reason* array is reporting Success.
There is a separate category to show locations with No Valid Scenarios / No Covering Cells.

Terminal Info: Tech Type (Failed)
Dependencies: Terminal, Snapshots, Other Tech

This array shows the failed technology type (GSM, UMTS, LTE or Wi-Fi) where
the *Terminal Info (GSM): Failure Reason* array is not reporting Success or
the *Terminal Info (UMTS): Failure* Reason array not reporting Success or
the *Terminal Info (LTE): Failure Reason* array not reporting Success or
the *Terminal Info (Wi-Fi): Failure Reason* array not reporting Success.
There is a separate category to show locations with No Valid Scenarios / No Covering Cells.

Terminal Info: Percentage Served
Dependencies: Terminal, Snapshots, Other Tech

This category comprises five arrays. The presence of the individual array instances depends on the technology types that are included in the simulation.
Terminal Info: Percentage Served (GSM)
Terminal Info: Percentage Served (UMTS)
Terminal Info: Percentage Served (LTE)
Terminal Info: Percentage Served (Wi-Fi)
Terminal Info: Percentage Served (No Tech)

After a terminal has been evaluated in a snapshot, it will be marked by precisely one technology type or as ‘No Tech’. The value shown at a pixel is determined by the all terminals that were attempted there, regardless of the snapshot in which they were attempted.

$$Percentage\ Served\ \left(Tech_J\right) = \frac{Served\ Attempts\ on\ Tech_J}{Total\ Attempts}\ ,$$

where $Tech_J = \{GSM, UMTS, LTE, Wi\text{-}Fi, NoTech\}$ and $\sum_J Percentage\ Served\ \left(Tech_J\right) = 1$.

5.15 Simulator Reports

Reports depicting the network performance are available after running the Monte Carlo Simulator in the snapshot mode. This section presents the available network performance reports and their description.

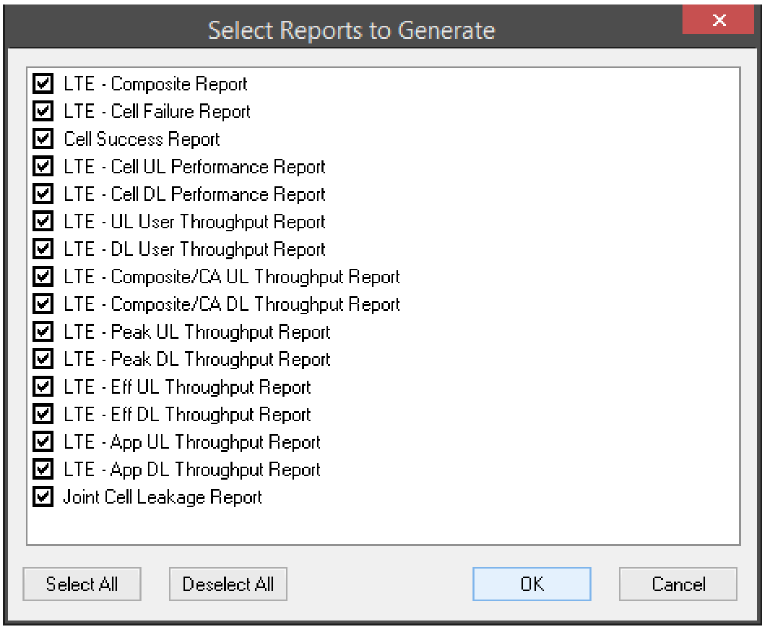


Figure 12: Available Network analysis reports

LTE - Composite Report
Dependencies: Service

This report provides the summary of each service in terms of 'Mean Attempted', 'Mean Served' and 'Mean Failed', terminals. The 'Contribution to Failure' section lists the possible reasons, as explained in section 4.2, and their percentages that contribute to terminals not being served. Terminals can fail to connect for multiple reasons so the failure reason percentages can sum to more than 100%.

LTE - Cell Failure Report
Dependencies: Service

This provides a breakdown of the 'Composite Report' and lists the per cell failure reasons for 'Mean Failed', terminals. Failure reasons and their respective percentages that contribute to terminals not being served are logged against each cell and per service.

Cell Success Report
Dependencies: Service

This report provides the breakdown of per cell successfully served terminals in UL and DL. It includes cells of other technologies that are present in the simulation.

LTE - Cell Uplink Performance Report
Dependencies: Carrier

This report provides the per carrier UL interference level and resource consumption information for each cell. UL Interference levels and resource consumptions are logged individually for CC and CE bandwidth partitions i.e. 'CC Interference Level (dB)', 'CE Interference Level (dB)', 'CC Load (%)' and 'CE Load (%)'. The interference levels can be applied to Site Database and further used in creating arrays by running the Simulator in the 'Load levels specified in database' mode. CE loads and

interference levels are only applicable for the *Soft Frequency Reuse* and *Reuse Partitioning* ICIC schemes.
Note: '***' is used within this report to highlight any cell not employing the ICIC schemes or configured in a way that results in either a zero CC or CE bandwidth.

LTE - Cell Downlink Performance Report
Dependencies: Carrier

This report provides the per carrier DL power/resource consumption information for each cell. The breakdown of each cell 'Total Power' is given in terms of 'Fixed Channels Power' and 'Traffic & Control Power'. The former includes the power consumed by DL Signals and non-load-dependent Channels (DLRS, P-SCH, S-SCH, PBCH, PMCCH). 'Traffic & Control Power' includes the power consumed by the load-dependent Channels PDSCH and PDCCH. In addition, the resource consumption is logged individually for CC and CE bandwidth partitions i.e. 'CC Load (%)' and 'CE Load (%)'. These loads represent the respective resource consumption from the total/available CC and CE resources and can be applied to Site Database to be used further in creating arrays by running the Simulator in the 'Load levels specified in database' mode. CE loads are only applicable for the *Soft Frequency Reuse* and *Reuse Partitioning* ICIC schemes.
Note: '***' is used within this report to highlight any cell not employing the ICIC schemes or configured in a way that results in either a zero CC or CE bandwidth.

5.15.1 Throughput Reports

The available throughput reports are tiered at Peak, Effective and Application level, and the generic relation between the levels is given by:

$$\text{Application}_R = \text{ServiceRate}$$
$$\text{Effective}_R = \text{Application}_R \cdot [\,(1+ \text{ServiceOverheads}) \cdot (1+ \text{TTIbundlingOverheads})\,]$$
$$\text{Peak}_R = \text{Effective}_R \,/\, (1- \text{ErrorRate})$$

LTE - UL / DL User Throughput Report (kbps)
Dependencies: Service

These reports provide the per cell average user throughputs for each service. The peak, effective and application user throughputs are reported. The breakdown is given in terms of service area (CC/CE).

LTE - UL / DL Composite Throughput Report (kbps)
Dependencies: Service

These composite reports provide the summary of per cell offered and served throughput for a given service. Offered throughput of a cell is calculated as the MBR rate of the service increased by the service and TTI bundling overheads and multiplied by 'Mean number of Attempts'. First the GBR demands of terminals are attempted and if resources are still available to allocate, terminals are upgraded to serve potentially up to their MBR demands. Summary of throughputs are presented for 'Peak' (at physical layer), 'Effective' and 'Application' levels. In addition, these throughputs are reported for the CC and CE areas of the cells which are governed by the 'Cell Edge Thresholds' settings on the Site Database.

LTE - UL / DL CA (Intra) Throughput Report (kbps)

These CA reports provide the summary of served throughput for a given service processed at the logical Intra-eNodeB CA-group level, for carrier-aggregated cells belonging to the same eNodeB. These throughputs are reported for the CC and CE areas of the cells and are separated for SC (Single Carrier) connections and CA (Carrier Aggregation) connections.

LTE - UL / DL CA (Inter) Throughput Report (kbps)

These CA reports provide the summary of served throughput for a given service processed at the logical Inter-eNodeB CA-group level, for carrier-aggregated cells belonging to multiple eNodeBs. These throughputs are reported for the CC and CE areas of the cells.

LTE - UL / DL Cell Throughput Type Report (kbps)

These CA reports provide the summary of served throughput per cell for a given service. The Total cell throughputs are separated for SC (Single Carrier) connections, CA Intra (Intra-eNodeB Carrier Aggregation) connections and CA Inter (Inter-eNodeB Carrier Aggregation) connections. Summary of throughputs are presented for 'Peak' (at physical layer), 'Effective' and 'Application' levels.

LTE - UL/DL Peak Throughput Report (kbps)
Dependencies: Service, Bearer

These reports provide the breakdown of per cell served peak, at physical layer, throughputs for each service. The breakdown is given in terms of service area (CC/CE) as well as the served peak throughput by each bearer in respective CC and CE regions.

LTE - UL/DL Effective Throughput Report (kbps)
Dependencies: Service, Bearer

These reports provide the breakdown of per cell served effective throughputs for each service. The breakdown is given in terms of service area (CC/CE) as well as the served effective throughput by each bearer in respective CC and CE regions.

LTE - UL/DL Application Throughput Report (kbps)
Dependencies: Service, Bearer

These reports provide the breakdown of per cell served application throughputs for each service. The breakdown is given in terms of service area (CC/CE) as well as the served application throughput by each bearer in respective CC and CE regions.

Joint Cell Leakage Report
Dependencies: Service

This report provides the percentage of terminals that are leaking towards technology types other than the primary technology due to capacity failures. The primary technology is determined by the *Composite: Best Server* array. The report provides a per cell breakdown for cells of all included technologies.

5.15.2 Beamformer Reports

LTE - UL Beamformer Report

This report gives the angular distribution of UL SINR beamforming gain for all the beamformers in the simulation. Note that if a cell has multiple antennas, or is using an ICIC scheme where the carrier bandwidth has been split into cell-centre and cell-edge partitions, then this simulator will have a beamformer for each combination of antenna and carrier partition.

Values for the UL SINR beamforming gain are reported at a predetermined set of azimuthal angles with respect to the serving antenna, with the angles measured clockwise from North and incremented in 5 degree steps. By selecting a row of these values, Excel can be used to produce a radar plot (i.e. polar plot) of the UL SINR beamforming gain.

LTE – DL Beamformer Report

This report gives the angular distribution of DL interfering traffic power gain for all the beamformers in the simulation. Note that if a cell has multiple antennas, or is using an ICIC scheme where the carrier bandwidth has been split into cell-centre and cell-edge partitions, then this simulator will have a beamformer for each combination of antenna and partition

The values in the report take into account the proportion of DL load due to users served by DL beamforming. As the proportion of beamformed load decreases to zero, the overall power gain approaches unity.
The values are reported at a predetermined set of azimuthal angles with respect to the serving antenna, with the angles measured clockwise from North and incremented in 5 degree steps. By selecting a row of these values, Excel can be used to produce a radar plot (i.e. polar plot) of the overall DL interfering traffic power gain.

6 INTER CELL INTERFERENCE COORDINATION

A key aspect of LTE systems is that they can suffer from inter-cell interference, especially near the cell edges. Therefore some form of inter-cell interference management is crucial. Inter-Cell Interference Coordination (ICIC) schemes aim to maximize spectral efficiency of LTE systems by re-using the available resource blocks (RBs) as often and in as many cells as possible while keeping the overall ICI in the system to an acceptable level. There are various schemes that are designed to combat inter-cell interference, and their implementation in the live network scenario is largely governed by the equipment vendors. The following Inter-cell Interference Coordination (ICIC) schemes are supported in ASSET:

- Reuse 1 (Prioritisation)
- Soft Frequency Reuse
- Reuse Partitioning

Fundamental to each of these methods is a division of the network into two areas in relation to the cell coverage, i.e. Cell Centre Users (CCUs) and Cell Edge Users (CEUs). This spatial separation of cell service area is controlled in ASSET by the '*Cell Edge Thresholds*' defined on the *LTE Params* → *Thresholds* sub-tab in the Site Database. The available thresholds are '*RSRP*' and '*Relative RSRP*'. *RSRP* is self-explanatory while the latter is defined in dBs and can be expressed as the difference between the RSRPs of the serving and the strongest interfering cell.

Furthermore, the *Soft Frequency Reuse* and *Reuse Partitioning* schemes involve the division of carrier bandwidth (or RBs) into partitions dedicated for CCUs and CEUs. This bandwidth separation is controlled by the respective bandwidth settings, as explained in the relevant sections.

6.1 REUSE 1 (PRIORITISATION)

The simplest way to minimize ICI within a Frequency Reuse 1 (FR1) scenario is by prioritisation of resources. *Reuse 1 (Prioritisation)* scheme prioritises certain portions of the carrier bandwidth (i.e., number of RBs) in each cell according to a set plan. The whole bandwidth is still available for transmission in all cells, but the concept is that each cell uses its prioritised RBs more often than its non-prioritised RBs, so that it minimises the interference that it may cause to other cells.

Considering a typical three sectored LTE eNodeB, one third of the RBs can be prioritized in each sector according to a frequency plan. Under low load conditions, a sector will only use its own prioritized PRBs while leaving the others interference-free. It is well known that FR 1 performs well at low load, and this kind of resource prioritization can make it perform even better as long as no neighbouring sector consumes more than its prioritized PRBs. However, at higher traffic loads this scheme is susceptible to excessive ICI and low cell-edge throughputs.

This picture shows an example where the bandwidth is divided into 3 partitions:

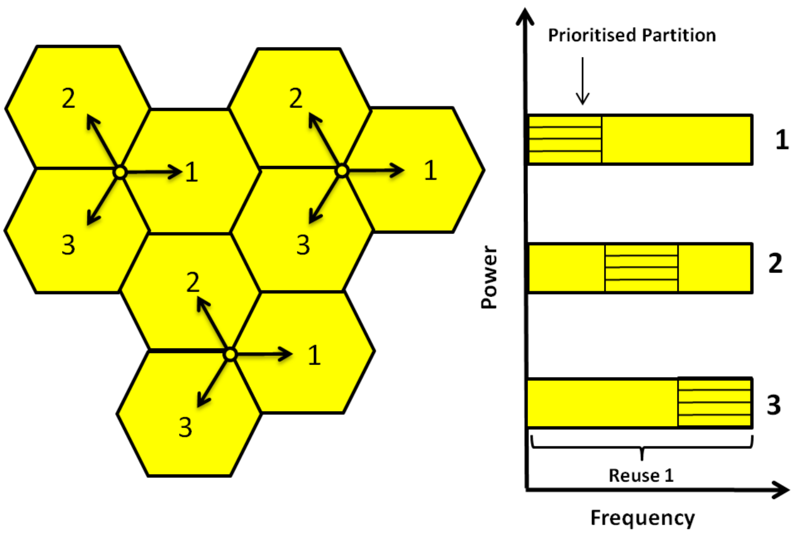


Figure 136: Reuse-1 Prioritisation

ASSET assumes that the RBs of a given transmission bandwidth (carrier) are always divided into three partitions that can be prioritised for both UL and DL. Interference reduction due to prioritisation is handled by introducing a scale factor for the interference. The scale factor accounts for the probability of RB collision between prioritised and non-prioritised partitions of interfering and victim cells. This interference scale factor depends on the load levels of the victim and interfering cell.

In an ideal system, interfering and victim cells have different prioritised partitions and the interference scale factor is given by

$$\Theta_{JC}^{diff} = 1 - \frac{\left(\overline{U_J} - 1\right)\left(\overline{U_C} - 1\right)}{(n-1)^2}\ , \tag{177}$$

where

$$\overline{U_J} = \min\left(n, \frac{1}{U_J}\right), \quad \overline{U_C} = \min\left(n, \frac{1}{U_C}\right). \tag{178}$$

where U_J and U_C are the load levels of the victim cell J and the interfering cell C. For simplicity, the same notations U_J and U_C have been used for the DL and UL load levels. The integer n is the number of prioritised partitions of the transmission bandwidth (carrier) and is fixed to three as this number provides the optimum trade off between the affordable complexity and interference reduction that can be achieved by using this scheme in realistic networks (*where majority of eNodeBs (sites) have three sectors each*).

The ideal interference scale factor represented by (177) is not always achievable in practice since not all interfering cells will have different prioritised partitions to the victim cell. A ‘coordination factor’ is introduced to control the unrealistic gains (*for very lightly loaded cells*) that can result from using (177) directly. This coordination factor can also be used to model various vendor specific coordination levels (*static, semi-static and dynamic*). With the introduction of a user-specified coordination factor φ_p^{CF} for the carrier p used by the cells, the interference scale factor becomes

$$\Theta_{JC}^{pri} = 1 - \varphi_p^{CF}\ \frac{\left(\overline{U_J} - 1\right)\left(\overline{U_C} - 1\right)}{(n-1)^2}. \tag{179}$$

The ICIC factor Θ_{JC}^{ICIC} when using the *Reuse 1 (Prioritisation)* scheme is therefore given by

$$\Theta_{JC}^{ICIC} = \Theta_{JC}^{pri}\ . \tag{180}$$

The factor Θ_{JC}^{ICIC} is used as follows in the downlink and uplink:

Downlink

The factor Θ_{JC}^{ICIC} is incorporated in the general expression for DL received interfering EPRE given by (51) . There it is written as $\Theta_{JC}^{v,a}$ to highlight dependence on victim and interfering subframe types in the DL.

Uplink

The factor Θ_{JC}^{ICIC} is incorporated in the UL (PUSCH/PUCCH) received interference expression given by (152).

Note: In ASSET, ICIC schemes are defined on the carrier level and further flexibility is available to enable/disable these schemes on the sector level. If no ICIC schemes are enabled on the carrier level then $\Theta_{JC}^{ICIC} = 1$. Also, if ICIC schemes are disabled on either the best server J or interfering sector C, then again $\Theta_{JC}^{ICIC} = 1$.

6.2 SOFT FREQUENCY REUSE

This scheme is an extension of the *Reuse-1 (Prioritisation)* scheme, where in addition to prioritising RBs in each cell, a **power difference** in the DL between Cell Centre Users (CCUs) and Cell Edge Users (CEUs) is also introduced. Also known as DL power planning, it exploits the fact that overall ICI in the network is not only dependent on how RBs are allocated but also to what extent and power these are used once allocated. This difference in power between RBs effectively divides the cell into an inner and an outer region, and the users located in these regions can be classified as the CCUs and CEUs, respectively. The CCUs can be served with the reduced power whereas CEUs require more power than CCUs for successful transmission. Hence, by prioritising and using more power on CEUs' RBs, overall ICI mitigation in the network and performance gain in terms of coverage and cell-edge capacity can be realized.

Regarding LTE network implementation, several versions of Soft Frequency Reuse schemes have been considered. All the proposed mechanisms depend on the division of the carrier bandwidth (RBs) into two portions, that is, specific portions of bandwidth prioritised for CCUs and CEUs, respectively. Some implementations allow transmission on all the available RBs (for both CCUs and CEUs), so that the entire spectrum will be used as soon as there is an eNodeB in the network that has enough data to fill all the RBs. Some implementations allow CEUs to consume the RBs of CCUs, but not the reverse. Other implementations do not allow any cross-consumption, and this is the implementation used in ASSET which can be summarized as:

- Split the carrier bandwidth (RBs) into two dedicated portions or zones, i.e. CC zone and CE zone, one for CCUs and the other for CEUs, using the '*Soft Bandwidth Ratio*' parameter.
- Specify a '*Coordination Factor*'. The Reuse-1 (Prioritisation) scheme (as described in the previous section) is implemented within both zones; each sector has a prioritised partition in each zone, which it tries to use before the non-prioritised partitions in that zone. The coordination factor can be used to adjust the interference reduction due to prioritisation for the CC and CE zones.
- Specify a power difference between the DL RBs of the CEUs and CCUs, using the '*Power Ratio*' parameter. The concept is that the CCUs can be reached with the reduced power whereas the CEUs need the higher power level for successful transmission. This results in a possible performance gain for the CEUs.

This picture shows an example of the *Soft Frequency Reuse* scheme:

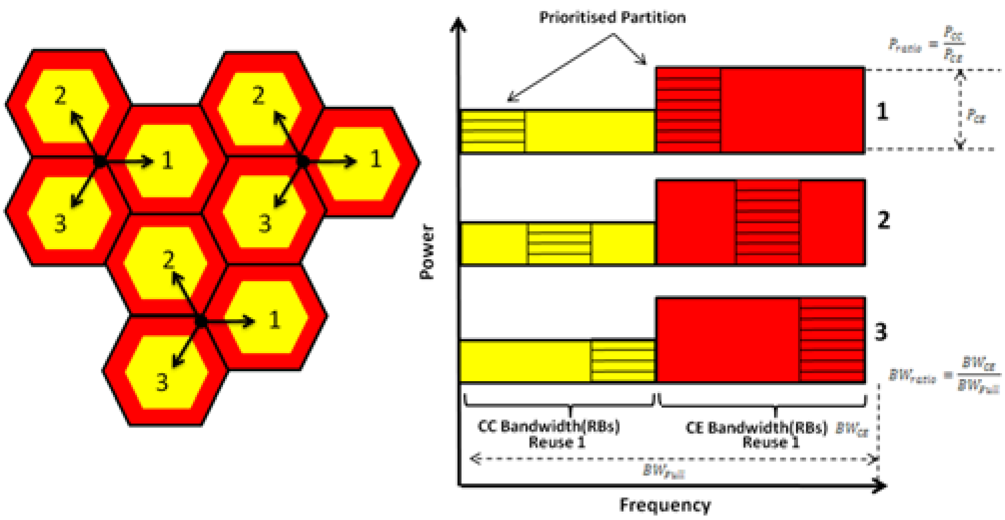


Figure 14: Soft Frequency Reuse Scheme

The user-specified 'Soft Bandwidth Ratio' of an LTE carrier p, which is defined as $\left(W_p^{CE} / W_p^{total}\right)$, is used to calculate the CC and CE bandwidth ratios for the *Soft Frequency Reuse* scheme as follows

$$\gamma_p^{soft\ CE} = \frac{W_p^{CE}}{W_p^{total}} \ , \qquad \gamma_p^{soft\ CC} = \frac{W_p^{CC}}{W_p^{total}} = 1 - \frac{W_p^{CE}}{W_p^{total}} = 1 - \gamma_p^{soft\ CE} \ , \tag{181}$$

where $\gamma_p^{soft,CC}$ and $\gamma_p^{soft,CE}$ are the CC and CE bandwidth ratios for carrier p.

The soft bandwidth ratios of (181) along with the 'DL Power ratio' of an LTE carrier p, which is defined as $\left(PPRE^{CC} / PPRE^{CE}\right)$, are used to determine the respective DL CC and CE EPREs for Traffic (PDSCH), Control (PDCCH) and Traffic/Control (PDSCH/PDCCH). This is achieved by introducing the CC and CE EPRE scaling factors given by

$$\begin{aligned} \zeta_p^{soft,CC} &= \frac{PPRE^{CC}}{\gamma_p^{soft,CC}\ PPRE^{CC} + \gamma_p^{soft,CE}\ PPRE^{CE}} \ , \\ \zeta_p^{soft,CE} &= \frac{PPRE^{CE}}{\gamma_p^{soft,CC}\ PPRE^{CC} + \gamma_p^{soft,CE}\ PPRE^{CE}} \ , \end{aligned} \tag{182}$$

The CC and CE EPRE scaling factors of (182) are used in the Downlink EPRE expressions of Traffic and Control channels to calculate the modified EPRE.

The CC and CE EPREs for the Control channel (PDCCH) can be expressed as

$$\varepsilon_{J,p,CC}^{CTRL,tx} = \varepsilon_{J,p}^{CTRL,tx}\ \zeta_p^{soft,CC} \ , \qquad \varepsilon_{J,p,CE}^{CTRL,tx} = \varepsilon_{J,p}^{CTRL,tx}\ \zeta_p^{soft,CE} , \tag{183}$$

where $\varepsilon_{J,p}^{CTRL,tx}$ is the EPRE of PDCCH for cell J employing carrier p as calculated via (116). When using *Soft Frequency Reuse* the respective CC and CE PDCCH EPREs given by (183) are used within CC and CE regions.

The CC and CE EPREs of the Traffic channel (PDSCH) can be expressed as

$$\varepsilon_{J,p,CC}^{traffic,tx} = \varepsilon_{J,p}^{traffic,tx}\ \zeta_p^{soft,CC} \ , \qquad \varepsilon_{J,p,CE}^{traffic,tx} = \varepsilon_{J,p}^{traffic,tx}\ \zeta_p^{soft,CE} , \tag{184}$$

where $\varepsilon_{J,p}^{traffic,tx}$ is the EPRE of PDSCH for cell J employing carrier p as calculated via (117). When using *Soft Frequency Reuse* the respective CC and CE PDSCH EPREs given by (184) are used within CC and CE regions.

The CC and CE EPREs for the Traffic/Control (PDSCH/PDCCH) can be expressed as

$$\varepsilon_{J,p,CC}^{traffic/CTRL,tx} = \varepsilon_{J,p}^{traffic/CTRL,tx}\ \zeta_p^{soft,CC} \ , \qquad \varepsilon_{J,p,CE}^{traffic/CTRL,tx} = \varepsilon_{J,p}^{traffic/CTRL,tx}\ \zeta_p^{soft,CE} , \tag{185}$$

where $\varepsilon_{J,p}^{traffic/CTRL,tx}$ is the EPRE of PDSCH/PDCCH for cell J employing carrier p as calculated via (118). When using *Soft Frequency Reuse* the respective CC and CE PDSCH/PDCCH EPREs given by (185) are used within CC and CE regions.

Once the CC and CE bandwidth with respective DL EPRE levels have been determined, the *Reuse 1 (Prioritization)* scheme as explained in previous subsection is implemented in both CC and CE zones and both link (DL/UL) directions.

In a similar manner to (179), the interference scale factors for prioritisation in the CC and CE zones are given by

$$\Theta_{JC}^{pri,CC} = 1 - \varphi_p^{CF} \frac{\left(\overline{U_J^{CC}} - 1\right)\left(\overline{U_C^{CC}} - 1\right)}{(n-1)^2} ,$$
$$\Theta_{JC}^{pri,CE} = 1 - \varphi_p^{CF} \frac{\left(\overline{U_J^{CE}} - 1\right)\left(\overline{U_C^{CE}} - 1\right)}{(n-1)^2} , \qquad \textbf{(186)}$$

where

$$\overline{U_J^{CC}} = \min\left(n, \frac{1}{U_J^{CC}}\right) , \quad \overline{U_C^{CC}} = \min\left(n, \frac{1}{U_C^{CC}}\right) ,$$
$$\overline{U_J^{CE}} = \min\left(n, \frac{1}{U_J^{CE}}\right) , \quad \overline{U_C^{CE}} = \min\left(n, \frac{1}{U_C^{CE}}\right) . \qquad \textbf{(187)}$$

U_J^{CC}, U_C^{CC}, U_J^{CE}, U_C^{CE} are the CC and CE load levels of the victim cell J and interfering cell C. For simplicity, the same notations (U_J^{CC}, U_C^{CC}, U_J^{CE}, U_C^{CE}) have been used for the DL and UL load levels. These load levels can be set on the Site Database or calculated by running the snapshots.

The integer n is the number of prioritised partitions of the transmission bandwidth (carrier) and is fixed to three for both CC and CE zones. Similarly to *Reuse 1 (Prioritization)*, a user-specified coordination factor φ_p^{CF} controls the degree of interference reduction due to prioritisation.

The ICIC factor Θ_{JC}^{ICIC} when using the *Soft Frequency Reuse* scheme is given by

$$\Theta_{JC}^{ICIC} = \begin{cases} \Theta_{JC}^{pri,CC} & \text{for the CC zone} \\ \Theta_{JC}^{pri,CE} & \text{for the CE zone} \end{cases} \qquad \textbf{(188)}$$

The factor Θ_{JC}^{ICIC} is used as follows in the downlink and uplink:

Downlink

The factor Θ_{JC}^{ICIC} is incorporated in the general expression for DL received interfering EPRE given by (51) . There it is written as $\Theta_{JC}^{v,a}$ to highlight dependence on victim and interfering subframe types in the DL.

Uplink

The factor Θ_{JC}^{ICIC} is incorporated in the UL (PUSCH/PUCCH) received interference expression given by (152).

Note: In ASSET, ICIC schemes are defined on the carrier level and further flexibility is available to enable/disable these schemes on the sector level. If no ICIC schemes are enabled on the carrier level then $\Theta_{JC}^{ICIC} = 1$. Also, if ICIC schemes are disabled on either the best server J or interfering sector C, then again $\Theta_{JC}^{ICIC} = 1$.

6.3 Reuse Partitioning

In addition to prioritization of RBs and different DL power levels, this scheme also divides the available spectrum into multiple partitions. Reuse Partitioning is similar to *Soft Frequency Reuse*, because it divides the available carrier bandwidth (RBs) into two dedicated zones, one for CCUs, and the other for CEUs. As in *Soft Frequency Reuse*, the CC zone uses *Reuse 1 (Prioritisation)*. However, unlike *Soft Frequency Reuse*, the CE zone does *not* use *Reuse 1 (Prioritisation)*, but instead employs the traditional frequency reuse of *N*, where *N* is the number of sectors on the eNodeB. Each sector can only consume CE resources from its own dedicated CE partition. Restricting each sector to its own dedicated CE partition results in power concentration for the CE partition which means that the spectral density of the power transmitted over a fraction of the CE RBs, is higher than the spectral density of the same power transmitted over the entire RBs.

The implementation used in ASSET can be summarized as:

- Split the carrier bandwidth (RBs) into two dedicated portions or zones, one for CCUs and the other for CEUs, using the *Bandwidth Ratio* parameter.
- Specify a *CC Coordination Factor* parameter. The *Reuse-1 (Prioritisation)* scheme (as described in the previous sections) is implemented within the CC zone. The coordination factor can be used to adjust the interference reduction due to prioritisation in the CC zone.
- Divide the CE zone into partitions. This normally relates to the number of sectors on the eNodeB, but it can be set to any value by using the *# CE Partitions* parameter. The CE zone employs the traditional frequency reuse of *N*, where *N* is the number of sectors on the eNodeB and each sector is tracked by its Physical Cell ID code.
- Specify a DL power difference between the RBs of the CEUs and CCUs, using the *Power Ratio* parameter. This is in addition to the power concentration effect resulting from the reuse *N* within the CE zone.

This picture shows an example of the Reuse Partitioning scheme:

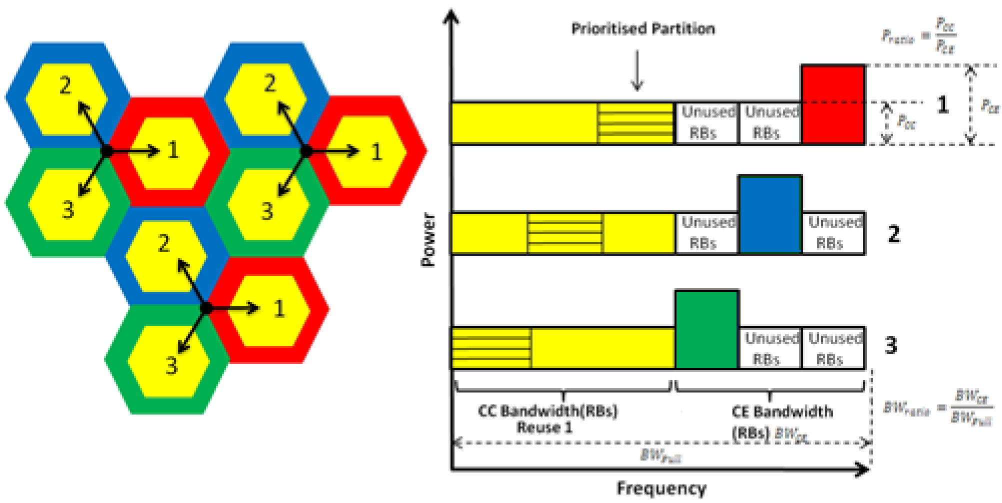


Figure 7: Reuse Partitioning Scheme

The user-specified 'Bandwidth Ratio' of an LTE carrier p, which is defined as $\left(W_p^{CE} / W_p^{total}\right)$, is used to calculate the CC and CE bandwidth ratios for the *Reuse Partitioning* scheme as follows

$$\gamma_p^{ru\,part,CE} = \frac{1}{N}\frac{W_p^{CE}}{W_p^{total}} \;, \qquad \gamma_p^{ru\,part,CC} = \frac{W_p^{CC}}{W_p^{total}} = 1 - \frac{W_p^{CE}}{W_p^{total}} = 1 - N\gamma_p^{ru\,part,CE} \;, \tag{189}$$

where $\gamma_p^{ru\,part,CC}$ and $\gamma_p^{ru\,part,CE}$ are the CC and CE bandwidth ratios and N is the *# CE Partitions* normally equal to number of sectors on the eNodeB.

The soft bandwidth ratios of (189) along with the 'DL Power ratio' of an LTE carrier p, which is defined as $\left(PPRE^{CC} / \, PPRE^{CE}\right)$, are used to determine the respective DL CC and CE EPREs for Traffic (PDSCH), Control (PDCCH) and Traffic/Control (PDSCH/PDCCH). This is achieved by introducing the CC and CE EPRE scaling factors given by

$$\zeta_p^{ru\,part,CC} = \frac{PPRE^{CC}}{\gamma_p^{ru\,part,CC}\, PPRE^{CC} + \gamma_p^{ru\,part,CE}\, PPRE^{CE}}\,,$$
$$\zeta_p^{ru\,part,CE} = \frac{PPRE^{CE}}{\gamma_p^{ru\,part,CC}\, PPRE^{CC} + \gamma_p^{ru\,part,CE}\, PPRE^{CE}}\,, \qquad \textbf{(190)}$$

Finally, the CC and CE EPRE scaling factors of (190) are used in the Downlink EPRE expression of Traffic and Control channels to calculate the modified EPREs.

The CC and CE EPRE for the Control channel (PDCCH) can be expressed as

$$\varepsilon_{J,p,CC}^{CTRL,tx} = \varepsilon_{J,p}^{CTRL,tx}\ \zeta_p^{ru\,part,CC}\,, \qquad \varepsilon_{J,p,CE}^{CTRL,tx} = \varepsilon_{J,p}^{CTRL,tx}\ \zeta_p^{ru\,part,CE}\,, \qquad \textbf{(191)}$$

where $\varepsilon_{J,p}^{CTRL,tx}$ is the EPRE of PDCCH for cell J employing carrier p as calculated via (116). When using *Soft Frequency Reuse* the respective CC and CE PDCCH EPREs given by (183) are used within CC and CE regions.

The CC and CE EPREs of the Traffic channel (PDSCH) can be expressed as

$$\varepsilon_{J,p,CC}^{traffic,tx} = \varepsilon_{J,p}^{traffic,tx}\ \zeta_p^{ru\,part,CC}\,, \qquad \varepsilon_{J,p,CE}^{traffic,tx} = \varepsilon_{J,p}^{traffic,tx}\ \zeta_p^{ru\,part,CE}\,, \qquad \textbf{(192)}$$

where $\varepsilon_{J,p}^{traffic,tx}$ is the EPRE of PDSCH for cell J employing carrier p as calculated via (117). When using *Soft Frequency Reuse* the respective CC and CE PDSCH EPREs given by (184) are used within CC and CE regions.

The CC and CE EPRE for the Traffic/Control (PDSCH/PDCCH) can be expressed as

$$\varepsilon_{J,p,CC}^{traffic/CTRL,tx} = \varepsilon_{J,p}^{traffic/CTRL,tx}\ \zeta_p^{ru\,part,CC}\,,$$
$$\varepsilon_{J,p,CE}^{traffic/CTRL,tx} = \varepsilon_{J,p}^{traffic/CTRL,tx}\ \zeta_p^{ru\,part,CE}\,, \qquad \textbf{(193)}$$

where $\varepsilon_{J,p,}^{traffic/CTRL,tx}$ is the EPRE of PDSCH/PDCCH for cell J employing carrier p as calculated via (118). When using *Soft Frequency Reuse* the respective CC and CE PDSCH/PDCCH EPREs given by (185) are used within CC and CE regions.

Once the CC and CE bandwidth with respective DL EPRE levels have been determined, the *Reuse 1(Prioritization)* scheme as explained in previous subsections is implemented in both UL and DL CC zone while static frequency reuse is used in the CE zone.

The ICIC factor Θ_{JC}^{ICIC} when using the *Reuse Partitioning* scheme is given by

$$\Theta_{JC}^{ICIC} = \begin{cases} \Theta_{JC}^{pri,CC} & \text{for CC zone} \\ B_{JC} & \text{for CE Zone} \end{cases}, \tag{194}$$

where $\Theta_{JC}^{pri,CC}$ is given by (186) and B_{JC} ensures that the CE partitions of different sectors interfere with each other if they are using the same or unassigned Physical Cell ID (PCI) Codes. This is achieved by tracking the partitions of eNodeB sectors with respect to the PCI Codes (*which are either 0, 1 or 2*) and the factor B_{JC} can be expressed as

$$B_{JC} = \begin{cases} 1 & J \text{ or } C \text{ have the same PCI code} \\ 0 & J \text{ or } C \text{ have the different PCI codes} \end{cases} \tag{195}$$

The factor Θ_{JC}^{ICIC} is used as follows in the downlink and uplink:

Downlink

The factor Θ_{JC}^{ICIC} is incorporated in the general expression for DL received interfering EPRE given by (51) . There it is written as $\Theta_{JC}^{v,a}$ to highlight a dependence on victim and interfering subframe types in the DL.

Uplink

The factor Θ_{JC}^{ICIC} is incorporated in the UL (PUSCH/PUCCH) received interference expression given by (152).

Note: In ASSET, ICIC schemes are defined on the carrier level and further flexibility is available to enable/disable these schemes on the sector level. If no ICIC schemes are enabled on the carrier level then $\Theta_{JC}^{ICIC} = 1$. Also, if ICIC schemes are disabled on either the best server J or interfering sector C, then again $\Theta_{JC}^{ICIC} = 1$.

7 Scheduling and Radio Resource Management

LTE support in ASSET follows a complex and state-of-the-art QoS architecture to replicate the scheduling and Radio Resource Management (RRM) methodologies of real networks. This includes service prioritisation based on the QoS Class Indicator (QCI) associated with each LTE service. It also includes the management and distribution of resources among the terminals, depending on the traffic type of the service. Different scheduling algorithms are available to determine the allocation of these resources and to simulate network capacity for a mixture of services/traffic types and varying load levels.

LTE services consist of two traffic types

- Real Time
- Non-Real Time

Real Time services and Non-Real Time service have an associated Maximum Bitrate (MBR) demand in addition to the (minimum) Guaranteed Bitrate (GBR).

When running a simulation, ASSET first attempts to serve the GBR demands of the services, taking into account the Priority values of the different services. Resources are first allocated to the service with the highest priority, and then to the next highest priority service, and so on. Terminals are only served if there are enough resources available to satisfy their GBR demand. In the event that there are not enough resources to fulfil the GBR demand of all Real Time and Non-Real Time services, then only the Priority values of the services determine the precedence of resource allocation.

If resources are still available after the GBR demands have been met, then different scheduling algorithms can be employed to attempt to upgrade the service rate in order to serve the MBR demands. This is where Scheduling and Radio Resource Management (RRM) are relevant. Here is an illustration:

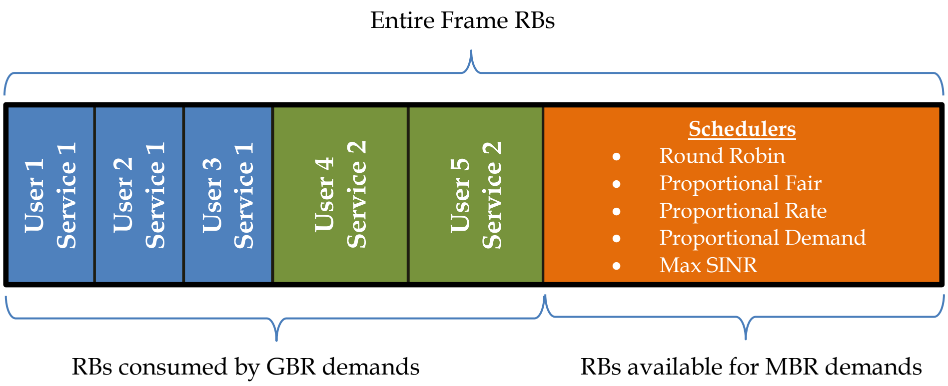


Illustration of Scheduling and RRM methodology

If MBR is set equal to GBR for a service, then as far as the GBR is served, no further upgrading of the service is rate is attempted.

To satisfy the MBR of the services, there are five different scheduling algorithms available:

- Round Robin
- Proportional Fair
- Proportional Rate
- Proportional Demand
- Max SINR

7.1 Round Robin

The aim of this scheduler is to share the remaining unused resources equally among the terminals in order to satisfy their MBR demand. This is a recursive algorithm and continues to share resources equally among terminals, until all MBR demands have been met or there are no more resources left to allocate. This can be explained as follows:

The scheduler progressively increases the resource usage factors α_k^{DL} and α_k^{UL} allocated to terminals. At the start of the recursive procedure, terminals have resource usage factors corresponding to the minimum values $\alpha_{p,min}^{DL\,bearer,tx}$ and $\alpha_{p,min}^{UL\,bearer}$ given in (31) and (34) respectively. The recursion then proceeds as follows:

STEP 1: Calculate the DL and UL unused resources, $RE^{DL\,unused}$ and $RE^{UL\,unused}$.

STEP 2: If there are a total of K upgradeable terminals, then the kth terminal is assigned extra resources given by

$$\begin{aligned} &\min\left(\Omega_k^{DL}, \frac{RE^{DL\,unused}}{K}\right), && \text{in the DL} \\ &\min\left(\Omega_k^{UL}, \frac{RE^{UL\,unused}}{K}\right), && \text{in the UL} \end{aligned} \tag{196}$$

where the additional resource demands Ω_k^{DL} and Ω_k^{UL} are given by

$$\Omega_k^{DL} = RE_p^{DL\,traffic}\left[\alpha_{p,max}^{DL\,bearer,tx} - \alpha_k^{DL}\right], \tag{197}$$

and

$$\Omega_k^{UL} = RE_p^{UL\,traffic}\left[\min\left(\alpha_{Cap}, \alpha_{p,max}^{UL\,bearer}\right) - \alpha_k^{UL}\right], \tag{198}$$

where $\alpha_{p,max}^{DL\,bearer,tx}$ and $\alpha_{p,max}^{UL\,bearer}$ are the maximum resource usages given in (18) and (20) respectively. Finally, α_{Cap} which is only applicable in the UL is defined as the maximum resource usage that can be assigned in the UL while maintaining coverage.

STEP 3: Go to STEP 1.

7.2 Proportional Fair

The aim of this Scheduler is to allocate the remaining unused resources as fairly as possible in such a way that, on average, each terminal gets the highest possible throughput achievable under the channel conditions.

This scheduler builds on the principles of the Round Robin scheduler and additionally exploits the fast fading characteristics of the propagation channel by resourcefully choosing the most favourable (in terms of radio conditions) users for transmission at each instant. The effect of transmitting at instants of positive fade can result in reduced average resource consumption because higher data rates are instantaneously achieved. As a result of this scheduling algorithm, a Multi User Gain is achieved.

7.2.1 Multi User Gain

The Multi User Gain for terminal k is given by:

$$MUG_k^{DL} = 1 + f_{J,k}^{NRA}\ g_{J,k}^{DL,\ SINR\,\&\,MIMO}\ g_J^{N-Users}$$
$$MUG_k^{UL} = 1 + f_{J,k}^{NRA}\ g_{J,k}^{UL,\ SINR\,\&\,MIMO}\ g_J^{N-Users} \quad (199)$$

where

$f_{J,k}^{NRA}$ is the 'MUG non-Rayleigh Adjustment' for cell J at the location of terminal k. The Multi User Gain for Proportional Fair scheduler relies on a low correlation between the signal paths to the antenna elements (Rayleigh environment). Locations that are in Line of Sight or that have high SINR are more likely to have highly correlated signal paths (non-Rayleigh environment). If the cell is using the Proportional Fair scheduler, you can select options to adjust the Multi User Gain under non-Rayleigh conditions in the *MUG non-Rayleigh Adjustment for Proportional Fair* cell parameters. If the options are not set or if the terminal is in Rayleigh conditions then $f_{J,k}^{NRA}$ is 1.

$g_{J,k}^{DL/UL,SINR\,\&\,MIMO}$ is the 'MUG SINR & MIMO Dependence' that is the Multi User Gain Dependence on Traffic & Control SINR conditions and MIMO order for terminal k served by cell J, in the downlink and in the uplink respectively. This is an internal table of values for all applicable DL and UL MIMO configurations and SINR ranges. This table can be overridden by one generic value by selecting the 'Override SINR and MIMO Dependence' option and setting a value in *Configuration → Lookup Tables and Curves → LTE PF Scheduler Multi User Gain*.

$g_J^{N-Users}$ is the 'MUG Number-of-Users Dependence' that is a function of the number of served users by cell J. The values for 'MUG Number-of-Users Dependence' are specified in *Configuration → Lookup Tables and Curves → LTE PF Scheduler Multi User Gain*.

The reduced average resource consumption due to the instantaneously higher data rates for terminal k for a bearer configured for carrier p is given by:

$$\alpha_{p,k}^{DL\,bearer,tx,MUG} = \frac{\alpha_p^{DL\,bearer,tx}}{MUG_k^{DL}},$$
$$\alpha_{p,k}^{UL\,bearer,tx,MUG} = \frac{\alpha_p^{UL\,bearer,tx}}{MUG_k^{UL}} \quad (200)$$

7.3 Proportional Rate

The aim of this Scheduler is to allocate the remaining unused resources in proportion to the achievable bearer data rate under the channel conditions.

This is a recursive algorithm. The remaining resources are shared between the terminals in proportion to their bearer data rates. Terminals with higher data rates get a larger share of the available resources. Each terminal gets either the resources it needs to satisfy its MBR demand, or its weighted portion of the available/unused resources, whichever is smaller. This recursive allocation process continues until all MBR demands have been met or there are no more resources left to allocate.

The scheduler progressively increases the resource usage factors α_k^{DL} and α_k^{UL} allocated to terminals. At the start of the recursive procedure, terminals have resource usage factors corresponding to the minimum values $\alpha_{p,min}^{DL\,bearer,tx}$ and $\alpha_{p,min}^{UL\,bearer}$ given in (31) and (34) respectively. The recursion then proceeds as follows:

STEP 1: Calculate the DL and UL unused resources, $RE^{DL\,unused}$ and $RE^{UL\,unused}$.

STEP 2: Each upgradeable terminal k is assigned extra resources given by

$$\min\left(\Omega_k^{DL}\,,\; RE^{DL\,unused}\left(\frac{R_k^{DL\,bearer,tx}}{\sum_i R_i^{DL\,bearer,tx}}\right)\right), \qquad \text{in the DL}$$
$$\min\left(\Omega_k^{UL}\,,\; RE^{UL\,unused}\left(\frac{R_k^{UL\,bearer,tx}}{\sum_i R_i^{UL\,bearer,tx}}\right)\right), \qquad \text{in the UL} \tag{201}$$

where the additional resource demands Ω_k^{DL} and Ω_k^{UL} are given by

$$\Omega_k^{DL} = RE_p^{DL\,traffic}\left[\alpha_{p,max}^{DL\,bearer,tx} - \alpha_k^{DL}\right], \tag{202}$$

and

$$\Omega_k^{UL} = RE_p^{UL\,traffic}\left[\min\left(\alpha_{Cap}\,, \alpha_{p,max}^{UL\,bearer}\right) - \alpha_k^{UL}\right], \tag{203}$$

where $\alpha_{p,max}^{DL\,bearer,tx}$ and $\alpha_{p,max}^{UL\,bearer}$ are the maximum resource usages given in (31) and (34) respectively. Finally, α_{Cap} which is only applicable in the UL is defined as the maximum resource usage that can be assigned in the UL while maintaining coverage.

STEP 3: Go to STEP 1.

7.4 Proportional Demand

The aim of this scheduler is to allocate the remaining unused resources to terminals in proportion to their additional resource demands. This is a non-recursive allocation process and results in either satisfying the MBR demands of all terminals or the consumption of all of the resources. This resource allocation is done in two steps:

STEP 1: Calculate the DL and UL unused resources, $RE^{DL\,unused}$ and $RE^{UL\,unused}$.

STEP 2: Each of the upgradeable terminal is k assigned extra resources given by

$$\begin{cases} \min\left(\Omega_k^{DL}\ ,\ RE^{DL\,unused}\left(\frac{\Omega_k^{DL}}{\sum_i \Omega_i^{DL}}\right)\right), & \text{in the DL} \\ \min\left(\Omega_k^{UL}\ ,\ RE^{UL\,unused}\left(\frac{\Omega_k^{DL}}{\sum_i \Omega_i^{DL}}\right)\right), & \text{in the UL} \end{cases}, \quad \textbf{(204)}$$

where the additional resource demands Ω_k^{DL} and Ω_k^{UL} are given by

$$\{\Omega_k^{DL} = RE_p^{DL\,traffic}\left[\alpha_{p,max}^{DL\,bearer,tx} - \alpha_k^{DL}\right], \quad \textbf{(205)}$$

and

$$\Omega_k^{UL} = RE_p^{UL\,traffic}\left[\min\left(\alpha_{Cap}\ ,\alpha_{p,max}^{UL\,bearer}\right) - \alpha_k^{UL}\right]\ , \quad \textbf{(206)}$$

where $\alpha_{p,max}^{DL\,bearer,tx}$ and $\alpha_{p,max}^{UL\,bearer}$ are the maximum resource usages given in (31) and (34) respectively. Finally, α_{Cap} which is only applicable in the UL is defined as the maximum resource usage that can be assigned in the UL while maintaining coverage.

7.5 MAX SINR

The aim of this Scheduler is to maximise the average cell throughput. This is a non-recursive resource allocation process where terminals with higher bearer rates (and consequently higher SINR) are preferred over terminals with lower bearer rates (and consequently lower SINR). This means that resources are allocated first to those terminals with better SINR/channel conditions, thereby maximising the throughput. The extra resources allocated to the *k*th upgradeable terminal are given by

$$\begin{cases} \min\left(\Omega_k^{DL}\,,\ RE^{DL\,unused}\right), & \text{in the DL} \\ \min\left(\Omega_k^{UL}\,,\ RE^{UL\,unused}\right), & \text{in the UL} \end{cases} \qquad (207)$$

where the additional resource demands Ω_k^{DL} and Ω_k^{UL} are given by

$$\Omega_k^{DL} = RE_p^{DL\,traffic}\left[\alpha_{p,max}^{DL\,bearer,tx} - \alpha_k^{DL}\right]\,, \qquad (208)$$

and

$$\Omega_k^{UL} = RE_{p,q}^{UL\,traffic}\left[\min\left(\alpha_{Cap}\,,\alpha_{p,max}^{UL\,bearer}\right) - \alpha_k^{UL}\right] \quad , \qquad (209)$$

where $\alpha_{p,max}^{DL\,bearer,tx}$ and $\alpha_{p,max}^{UL\,bearer}$ are the maximum resource usages given in (31) and (34) respectively. Finally, α_{Cap} which is only applicable in the UL is defined as the maximum resource usage that can be assigned in the UL while maintaining coverage

7.6 TTI BUNDLING

TTI Bundling Gain is typically relevant to Voice over LTE (VoLTE) services. In simulations, it will offset and make the SINR requirements of the supported bearers for the service more easily achievable, thus realising a gain. In that context, TTI bundling is mostly relevant to the UL direction and with typical gain values in the range of 2 to 4 dB. The TTI Bundling Gain parameters in the UL and DL directions can be generically used to model other service-specific adjustments, which can be positive or negative offsets, to the SINR requirements of the supported bearers for any LTE service. TTI Bundling Gains are only applicable to terminals served by cells which support TTI Bundling. This cell parameter exists on the Scheduling subtab of the LTE Params tab for a cell in the Site Database. If TTI Bundling is used, there is additional Service Rate Overhead to account for the increased data rate incurred at physical layer, and therefore the increased resource consumption at physical layer, due to the redundancy versions of the same set of data that are transmitted in consecutive TTIs.

The increased data rate incurred at physical layer is described in (29) and the increased resource consumption, due to TTI bundling, is described in (31), (32), (34) and (35) for DL and UL.

The modified SINR requirement of the bearers in DL and UL is given by

$$SINR_{req}^{DL\,bearer,TTIb}(dB) = SINR_{req}^{DL\,bearer}(dB) + SINR_{TTIb\,gain}^{DL\,bearer}(dB)\,, \qquad (210)$$

and

$$SINR_{req}^{UL\,bearer,TTIb}(dB) = SINR_{req}^{UL\,bearer}(dB) + SINR_{TTIb\,gain}^{UL\,bearer}(dB)\,, \qquad (211)$$

where $SINR_{req}^{bearer}$ is the bearer's SINR requirement after any modifications for SU-MIMO Spatial Multiplexing, SU-MIMO Spatial Diversity, MU-MIMO or beamforming, and any clutter specific adjustments as described in chapter 8 Advanced Antenna Systems. $SINR_{TTIb\,gain}^{bearer}$ is the TTI bundling gain as specified in the service definition.

8 ADVANCED ANTENNA SYSTEMS

Advanced Antenna Systems (AAS) such as Single-User (SU) MIMO and Multi-User (MU) MIMO architecture is the key for providing higher peak data rates and improved coverage in LTE systems. SU-MIMO refers to all spatial diversity and multiplexing schemes where the MIMO channel is solely assigned to a single user/terminal. In contrast, MU-MIMO employs the same time-frequency resources to serve multiple users/terminals.

The following AAS modes are supported in ASSET for both link directions:

- SU-MIMO
  - Spatial Multiplexing (SM)
  - Spatial Diversity (SD) for transmit and/or receive.
  - Adaptive Switching between (SD and SM)
- MU-MIMO
- Beamforming

Certain modes can be combined as described in the section on mode selection. Note that beamforming is covered in detail in a separate section of this document.

8.1 SU-MIMO

This includes spatial multiplexing (SM), spatial diversity (SD) and the adaptive switching between these two MIMO modes. Release 9 of 3GPP standards supports spatial multiplexing only in DL, however ASSET allows the users to model all modes of SU-MIMO in both link directions. This is due to the fact that spatial multiplexing in the UL will be supported in future releases.

8.1.1 Spatial Multiplexing (SM)

This increases the per user data rate/throughput by transmitting multiple streams of data dedicated for a single user from multiple antennas at the transmitter and receiver sides. LTE DL transmission modes support closed-loop and open-loop spatial multiplexing (SM). The former requires the availability of both the Precoding Matrix Indicator (PMI) and Rank Indicator (RI) whereas the latter requires only the RI. Assuming the path gains between individual antenna pairs are independent and identically distributed (i.i.d.) Rayleigh distributed, a SM rate gain G^{SM} can be realized in the high $SINR$ regime, where $G^{SM} = \min(N^{tx}, N^{rx})$ with N^{tx} and N^{rx} are the number of transmit and receive antennas respectively.

In ASSET, the special multiplexing gain (*enhanced data rate*) G^{SM} is modelled by modifying the minimum and maximum resource consumptions/usage of DL and UL bearers i.e. $\alpha_{p,min}^{DL\,bearer,tx}$, $\alpha_{p,max}^{DL\,bearer,tx}$, $\alpha_{p,min}^{UL\,bearer}$, $\alpha_{p,max}^{UL\,bearer}$ as calculated in (31) and (34) respectively. The modified minimum and maximum resource consumptions in the DL and UL can be expressed as:

$$\alpha_{p,min}^{DL\,bearer,tx,SM} = \frac{\alpha_{p,min}^{DL\,bearer,tx}}{G^{SM,DL}\, C_{corr}^{SM,DL}} \quad \text{and} \quad \alpha_{p,max}^{DL\,bearer,tx\,,SM} = \frac{\alpha_{p,max}^{DL\,bearer,tx}}{G^{SM,DL}\, C_{corr}^{SM,DL}}\,, \tag{212}$$

and

$$\alpha_{p,min}^{UL\,bearer,tx,SM} = \frac{\alpha_{p,min}^{UL\,bearer,tx}}{G^{SM,UL}\, C_{corr}^{SM,UL}} \quad \text{and} \quad \alpha_{p,max}^{UL\,bearer,tx\,,SM} = \frac{\alpha_{p,max}^{UL\,bearer,tx}}{G^{SM,UL}\, C_{corr}^{SM,UL}}\,, \tag{213}$$

where $\alpha_{p,min}^{DL\,bearer,tx\,,SM}$, $\alpha_{p,max}^{DL\,bearer,tx\,,SM}$, $\alpha_{p,min}^{UL\,bearer,SM}$ and $\alpha_{p,max}^{UL\,bearer,SM}$ are the modified DL and UL minimum and maximum resource consumptions/usage when employing SM. $G^{SM,DL}$ and $G^{SM,UL}$ are SM gain values read from the respective UL and DL '*SM Rate Gain*' tables. The provided default values relate to the theoretical maximum possible throughput gain that can be achieved by employing given numbers of transmit and receive antennas at the eNodeB and terminals (*and vice versa*). Finally, $C_{corr}^{SM,DL}$ and $C_{corr}^{SM,UL}$ are the clutter specific DL and UL rate gain adjustments.

In addition to SM rate gain, ASSET also models the change in bearers' SINR requirements when using SM, i.e. a higher/lower SINR requirement of bearers as compared to single antenna transmission. These modified DL and UL bearers requirements can be expressed as (in dBs)

$$SINR_{req}^{DL\ bearer,SM}(dB) = SINR_{req}^{DL\ bearer}(dB) + SINR_{SM\ delta}^{DL\ bearer}(dB) + SINR_{SM\ offset}^{DL,clutter}(dB)\,, \qquad (214)$$

and

$$SINR_{req}^{UL\ bearer,SM}(dB) = SINR_{req}^{UL\ bearer}(dB) + SINR_{SM\ delta}^{UL\ bearer}(dB) + SINR_{SM\ offset}^{UL,clutter}(dB)\,, \qquad (215)$$

where

$SINR_{req}^{DL\ bearer}$, $SINR_{req}^{UL\ bearer}$	DL & UL bearers' SINR requirements without SM
$SINR_{req}^{DL\ bearer,SM}$, $SINR_{req}^{UL\ bearer,SM}$	Modified DL & UL bearers SINR requirements with SM
$SINR_{SM\ delta}^{DL\ bearer}$, $SINR_{SM\ delta}^{DL\ bearer}$	DL & UL SU-MIMO (SM) bearers SINR deltas
$SINR_{SM\ offset}^{DL,clutter}$, $SINR_{SM\ offset}^{UL,clutter}$	DL & UL clutter specific SM SINR offsets

8.1.2 Spatial Diversity (SD)

These techniques improve the SINR by transmitting the same stream of single user data from multiple antennas at the transmitter, receiver or both sides. Assuming the path gains between individual antenna pairs are i.i.d. Rayleigh distributed, a maximal diversity gain/order of G^{SD} can be achieved which makes the average error probability to decay as $SINR^{-G^{SD}}$ at high SINRs, in contrast to the $SINR^{-1}$ for a single-antenna fading channel, where $G^{SD} = N^{tx} \times N^{rx}$, with N^{tx} and N^{rx} representing the number of transmit and receive antennas respectively.

In ASSET, spatial diversity gain/order G^{SD} is modelled by modifying the raw SINR requirements of DL and UL bearers. The modified requirements when employing SD can be expressed as

$$SINR_{req}^{DL\ bearer,SD} = \frac{SINR_{req}^{DL\ bearer}}{G^{SD,DL}C_{corr}^{DL,SD}} \quad \text{and} \quad SINR_{req}^{UL\ bearer,SD} = \frac{SINR_{req}^{UL\ bearer}}{G^{SD,UL}C_{corr}^{UL,SD}}\,, \qquad (216)$$

where $SINR_{req}^{DL\ bearer}$, $SINR_{req}^{UL\ bearer}$ and $SINR_{req}^{DL\ bearer,SD}$, $SINR_{req}^{UL\ bearer,SD}$ are the raw and modified DL and UL bearers' SINR requirements. $G^{SD,DL}$ and $G^{SD,UL}$ are SD orders/gain values read from the respective UL and DL '*SD SINR Adjustment*' tables. The provided default values relate to the theoretical maximum possible diversity order that can be achieved by employing given numbers of transmit and receive antennas at the eNodeB and terminals (*and vice versa*). Finally, $C_{corr}^{SD,DL}$ and $C_{corr}^{SD,UL}$ are the clutter specific DL and UL SD SINR adjustments.

8.1.3 Adaptive Switching

This enables the SM and SD to be implemented in an adaptive fashion which is vital to maximize throughput of LTE networks. Adaptive switching has to be enabled on both LTE cells and terminals. ASSET always attempts to utilise a bearer in SM mode before attempting SD for a given terminal. In addition to this, the cell level '*Adaptive SU-MIMO RS SNR*' threshold can be employed to control the switching from SM to SD and when enabled, SM is employed above the threshold while SD below the threshold.

8.2 MU-MIMO

This architecture serves multiple users (*separated in the spatial domain in both link direction*) sharing the same time-frequency resource. It employs multiple narrow beams to separate users in the spatial domain and can be considered as a hybrid of beamforming and spatial multiplexing. By scheduling multiple terminals, MU-MIMO serves more terminals with the same resources, which in turns increases the cell capacity/throughput. This is normally suitable for highly loaded cells and for scenarios where number of served terminals is more important than peak user data rates.

In ASSET, the MU-MIMO gain (*increased served terminals*) G^{MU} is modelled by modifying the minimum and maximum resource consumptions/usage of DL and UL bearers. i.e. $\alpha_{p,min}^{DL\,bearer,tx}$, $\alpha_{p,max}^{DL\,bearer,tx}$ $\alpha_{p,min}^{UL\,bearer}$, $\alpha_{p,max}^{UL\,bearer}$ as calculated in (31) and (34) respectively. The modified minimum and maximum resource consumptions in the DL and UL can be expressed as:

$$\alpha_{p,min}^{DL\,bearer,tx,MU} = \frac{\alpha_{p,min}^{DL\,bearer,tx}}{G^{MU,DL}} \quad \text{and} \quad \alpha_{p,max}^{DL\,bearer,tx,MU} = \frac{\alpha_{p,max}^{DL\,bearer,tx}}{G^{MU,DL}}\ , \tag{217}$$

and

$$\alpha_{p,min}^{UL\,bearer,tx,MU} = \frac{\alpha_{p,min}^{UL\,bearer,tx}}{G^{MU,UL}} \quad \text{and} \quad \alpha_{p,max}^{UL\,bearer,tx,MU} = \frac{\alpha_{p,max}^{UL\,bearer,tx}}{G^{MU,UL}}\ , \tag{218}$$

where $\alpha_{p,min}^{DL\,bearer,tx,MU}$, $\alpha_{p,max}^{DL\,bearer,tx,MU}$, $\alpha_{p,min}^{UL\,bearer,MU}$ and $\alpha_{p,max}^{DL\,bearer,tx,MU}$ are the modified DL and UL minimum and maximum resource consumptions/usage when employing MU-MIMO. $G^{MU,DL}$ and $G^{MU,UL}$ are cell specific '*Average Co-scheduled Terminals*'.

In addition to '*Average Co-scheduled Terminals*', ASSET also models the change in bearers' SINR requirements when using MU-MIMO. i.e. a higher/lower SINR requirement of bearers as compared to single antenna transmission. These modified DL and UL bearer requirements can be expressed as

$$SINR_{req}^{DL\,bearer,MU}(dB) = SINR_{req}^{DL\,bearer}(dB) + SINR_{MU\,delta}^{DL\,bearer}(dB) + SINR_{MU\,offset}^{DL,clutter}(dB)\ , \tag{219}$$

and

$$SINR_{req}^{UL\,bearer,MU}(dB) = SINR_{req}^{UL\,bearer}(dB) + SINR_{MU\,delta}^{UL\,bearer}(dB) + SINR_{MU\,offset}^{UL,clutter}(dB)\ , \tag{220}$$

where

$SINR_{req}^{DL\,bearer}$, $SINR_{req}^{UL\,bearer}$	DL & UL bearers' SINR requirements without MU-MIMO
$SINR_{req}^{DL\,bearer,MU}$, $SINR_{req}^{UL\,bearer,MU}$	Modified DL & UL bearers' SINR requirements with MU-MIMO
$SINR_{MU\,delta}^{DL\,bearer}$, $SINR_{MU\,delta}^{UL\,bearer}$	DL & UL MU-MIMO (SM) bearers SINR deltas
$SINR_{MU\,offset}^{DL,clutter}$, $SINR_{MU\,offset}^{UL,clutter}$	DL & UL clutter specific MU-MIMO SINR offsets

8.3 AAS Mode Selection

The Simulator will attempt to use the enabled AAS modes in sequence with a broad underlying aim of maximising throughput.

For any given bearer, the possible (composite) transmission modes are listed below and ranked from the most desirable to the least desirable. Generally speaking, SU-MIMO SM modes are preferred since they increase the data rate of the connection. If SM is not possible, then MU-MIMO modes are the next most preferred because although the data rate of the user is not improved, the overall cell capacity is used more effectively. If neither SM nor MU-MIMO, are possible then the aim is to improve the reliability of the link using through either a SINR improvement due to beamforming or through the use of SD or both.

Transmission Mode Ranking for a Specific Bearer
SU-MIMO SM
SU-MIMO SM + Beamforming
MU-MIMO
MU-MIMO + Beamforming
SU-MIMO SD + Beamforming
SU-MIMO SD
Single Antenna (i.e. No MIMO or Beamforming)

There exist cell-specific MIMO thresholds that can be enabled to control the range of MIMO modes. These thresholds will affect simulation results and should only be enabled by experienced/advanced users because they can cause suboptimal network performance.

Cell-Specific Threshold	**Effect of Cell-Specific Threshold**
Adaptive SU-MIMO	Any mode involving SM is not allowed ***below*** the specified threshold.
MU-MIMO	Any mode involving MU-MIMO is not allowed ***below*** the specified threshold.
Beamforming	Any mode involving Beamforming is not allowed ***above*** the specified threshold.

The threshold controlling parameter can be one of the following:

- DL RS SNR as given by (167)
- DL RS SINR as given by (168)
- DL Traffic SINR as given by (172)
- UL Traffic SINR as described in (5.5).
  Note that UL Traffic SINR is equal to UL Traffic/Ctrl SINR.

9 COVERAGE PROBABILITY CALCULATIONS

The coverage probability describes the probability of receiving a signal being of sufficient strength/quality given that it has been transmitted through a wireless channel where the signal is subject to large and small scale fading, e.g. shadow fading, fast fading and etc.

Coverage probabilities are calculated *analytically*.

The Simulator can run in two different modes

- Using Cell Load levels as specified in the Site Database
- Calculating Cell Load Levels by running snapshots

In the second mode coverage plots can be obtained after running a very small number of snapshots (typically 10s) and plots converge very quickly. If no snapshots have been run, then coverage plots are still available but they give the coverage probabilities in an unloaded system. The network is unloaded with respect to own technology type but is still considering any Inter-technology DL/UL Noise Rise Cell Loads from the Site Database

We introduce the following notation to represent the probability density function for a normally distributed random variable with mean μ and standard deviation σ.

$$N(x;\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right), \tag{221}$$

9.1 FADES IN THE SIMULATION SNAPSHOTS

Shadow fading is modelled in a snapshot by randomising the pathlosses experienced by the randomly scattered terminals. Shadow fades are log-normally distributed, and the user specifies the shadow fading standard deviation for indoor and outdoor terminals in each clutter type. In reality, the fades between a terminal and the cells that cover it will exhibit a degree of correlation. In particular, a terminal is likely to have similar fades to cells that are located on the same site. To account for this, the user specifies two parameters in the Monte Carlo Wizard:

- The normalised inter-site correlation coefficient c^{inter} which is the correlation between fades to cells on different sites.

i. The normalised intra-site correlation coefficient c^{intra} which is the correlation between fades to cells on the same site.

These two parameters must satisfy the constraints $0 \le c^{inter} \le c^{intra} \le 1$. For each randomly scattered terminal in a snapshot, a set of correlated fades to the covering cells is generated using the following procedure. All the random numbers mentioned below are independent and normally distributed with zero mean and unit variance, and σ is the standard deviation of the shadow fading at the pixel in dB.

- Generate a random number X.
- For each site I, generate a random number Y_I.
- For each cell J, generate a random number Z_J.

The fade (in dB) to cell J on site I is then set to

$$\sigma\left(\sqrt{c^{inter}}X+\sqrt{c^{intra}-c^{inter}}Y_I+\sqrt{1-c^{intra}}Z_J\right) \tag{222}$$

The above procedure is performed for each of the randomly scattered terminals at the beginning of a snapshot. Fades for different terminals are uncorrelated even if they are located in the same pixel.

9.2 FADES IN ARRAYS FOR MEAN VALUES

Arrays showing the mean level of a quantity (e.g. DL linkloss, RSRP, RSRQ, etc) are calculated with all fades set to 0 dB.

9.3 FADES IN COVERAGE ARRAY CALCULATIONS

DLRS RSRP Coverage Probability

In the absence of fading, let the DLRS RSRP (in Watts) for cell J be represented by R_J^{DLRS}. If cell J has a fade of F_J dB, then the DLRS RSRP is given by $R_J^{DLRS}\left(10^{-F_J/10}\right)$.

We can calculate a coverage probability for the DLRS RSRP as follows:

- Find the fade F_J that causes the DLRS RSRP to *exactly* satisfy the RSRP requirement specified on the terminal type. Call this fade F^*. Note that F^* may be positive or negative. Any fade bigger than F^* will give an inadequate RSRP.

Since F_J is normally-distributed with a mean of 0 dB and standard deviation of σ dB, the probability that $F_J > F^*$ is given by

$$P\left(F_J > F^*\right) = \int_{F^*}^{\infty} N(x; 0, \sigma)\, \partial F_J \qquad \textbf{(223)}$$

This is the probability that the DLRS RSRP does not meet the requirement.

RSRQ Coverage Probability

This is calculated by following the same approach as described above for the DLRS RSRP coverage probability.

10 INTER-TECHNOLOGY INTERFERENCE

10.1 INTRODUCTION

The Multiple Technology Simulator allows considering the effects of inter-carrier interference for carriers of the same technology and carriers of different technologies. The considered technologies are GSM, UMTS, LTE and Wi-Fi. The selection in Step 2 of the Simulator Wizard determines the technology types that are considered for the subsequent calculations.

Carriers can be fully, partially or non-overlapping. Non-overlapping carriers can still be adjacent, hence interfering with each other. The relative position of carriers is determined by their Low and High frequencies that specify the operative range of the carrier.

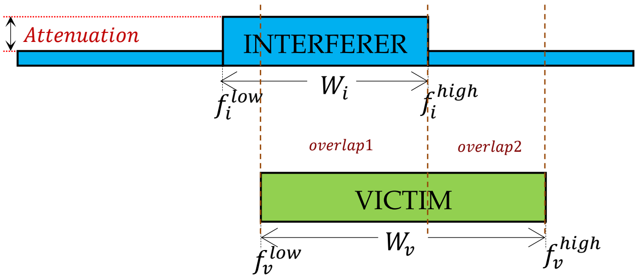


Figure 8: Illustration of overlapping carriers

The following figure is generic to all technology types.

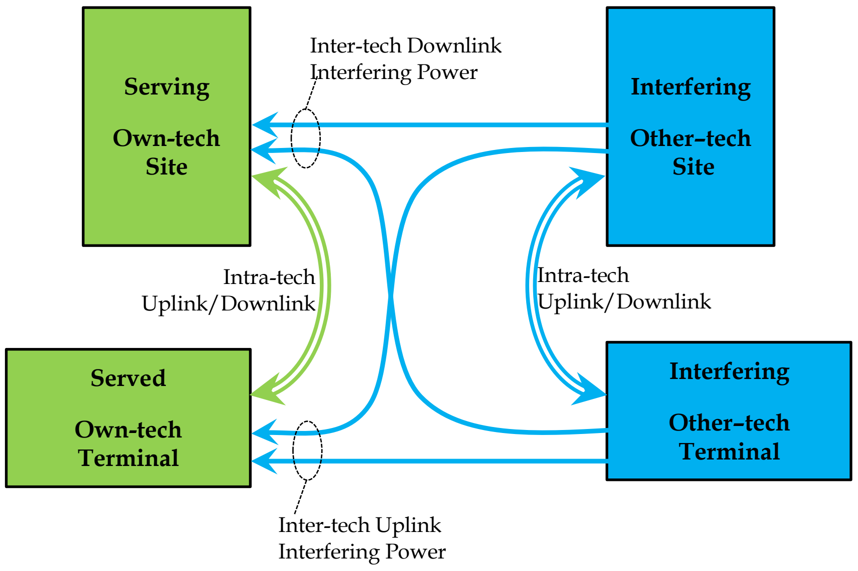


Figure 9: UL and DL Inter-technology Interference

Assuming LTE to be the reference technology in the context of the current document, the other interfering technologies can be GSM, UMTS and Wi-Fi.

Note: The uplink is not modelled for GSM and Wi-Fi, which means that GSM and Wi-Fi terminals' uplink transmission is not considered for interference.

10.2 Inter-Technology Interference Formulae

By selecting the appropriate option in the Simulator Wizard, carriers of the rest of the selected technologies are considered and the resulting inter-technology interference component is added to any intra-technology or own-technology interference.

$\sum_{tech \neq own}$ denotes the summation over the technologies that have been selected in the Simulator Wizard, excluding own, where $own = \{LTE\}$ and $other = \{GSM, UMTS, 5G, Wi\text{-}Fi\}$ in the context of the current document.

10.2.1 Uplink Received Interference

This is the interference received in the uplink by own cells and consists of two components

i. UL-UL: The uplink of $other$-technology terminals interfering with the uplink of own cells

ii. DL-UL: The downlink of $other$-technology cells interfering with the uplink of own cells

The combined effect of these two components is modelled via $NR_{J,p}^{UL,\ Tech}$, the Inter-technology UL Noise Rise due to cells and terminals of $other$ technologies and it is specified in the Site DB.

$$I_{J,p}^{UL\ inter\ tech} = \sum_{tech \neq own} (CP)_{J,p}^{tech} \times \left[(NR)_{J,p}^{UL\ tech} - 1\right] \times N_{J,p}^{UL}\ , \tag{224}$$

where

$I_{J,p}^{UL\ inter\ tech}$ is the inter-technology UL received interference power of cell J employing carrier p due to cells and terminals of $other$ technologies.

$(CP)_{J,p}^{tech}$ is the Channel Protection factor for the $other$ technologies and it is input from Site DB for cell J.

$(NR)_{J,p}^{UL\ tech}$ is the UL Noise Rise due to the $other$ technologies and it is input from Site DB for cell J.

$N_{J,p}^{UL}$ is the UL thermal noise power.

On the own cell, in Site DB, the combined inter-technology total UL Noise Rise, disregarding any Channel Protection factors, is reported as:

$$(NR)_{J,p}^{UL\ inter\ tech\ total} = 1 + \sum_{tech \neq own} \left[(NR)_{J,p}^{UL\ tech} - 1\right]. \tag{225}$$

On the own cell, in Site DB, the combined UL Noise Rise for all included technologies, disregarding any Channel Protection factors, is reported as:

$$(NR)_{J,p}^{UL\ all\ techs} = 1 + \sum_{tech = all} \left[(NR)_{J,p}^{UL\ tech} - 1\right]. \tag{226}$$

10.2.2 Downlink Received Interference

This is the interference received in the downlink by own terminals and consists of two components:

i. UL-DL: The uplink of $other$-technology terminals interfering with the downlink of own terminals

The effect of these this component is modelled via $(NR)_{J,p}^{DL\,tech\,terms}$, the inter-technology DL Noise Rise due to terminals of $other$ technologies and it is specified in the Site DB.

$$I_{J,p,k}^{DL\,inter\,tech\,terms} = \sum_{tech \neq own} (CP)_{J,p}^{tech} \times \left[(NR)_{J,p}^{DL\,tech\,terms} - 1\right] \times N_{p,k}^{DL} \ , \qquad \textbf{(227)}$$

where

$I_{J,p,k}^{DL\,inter\,tech\,terms}$ is the inter-technology DL received interference power for terminal k served by cell J employing carrier p due to terminals of $other$ technologies.

$(CP)_{J,p}^{tech}$ is the Channel Protection factor for the $other$ technologies and it is input from Site DB for cell J.

$(NR)_{J,p}^{DL\,tech\,terms}$ is the DL Noise Rise due to terminals of the $other$ technologies and it is input from Site DB for cell J.

$N_{p,k}^{DL}$ is the DL thermal noise power.

On the own cell, in Site DB, the combined inter-technology total DL Noise due to $other$-technology terminals, disregarding any Channel Protection factors, is reported as:

$$(NR)_{J,p}^{DL\,inter\,tech\,total\,terms} = 1 + \sum_{tech \neq own} \left[(NR)_{J,p}^{DL\,tech\,terms} - 1\right]. \qquad \textbf{(228)}$$

ii. DL-DL: The downlink of $other$-technology cells interfering with the downlink of the own terminals

The effect of this component is calculated as

$$I_{J,p,k}^{DL\,inter\,tech\,cells} = \sum_{tech \neq own} \sum_{q} (CP)_{J,p}^{tech} \ O_{pq}^{freq} \sum_{C \neq J} \frac{P_C}{L_{Ck}^{DL}} \ , \qquad \textbf{(229)}$$

where

$I_{J,p,k}^{DL\,inter\,tech\,cells}$ is the received DL interference power for terminal k served by cell J employing carrier p due to terminals of $other$ technologies.

$(CP)_{J,p}^{tech}$ is the Channel Protection factor for the $other$ technologies and it is input from Site DB for cell J.

O_{pq}^{freq} is the DL frequency overlap factor for victim carrier p and interfering carrier q.

P_C is the total time-average transmitted power of $other$-technology cell C.

L_{Ck}^{DL} is the link loss between $other$-technology cell C and own terminal k.

The summation of $I_{J,p,k}^{DL\ inter\ tech\ terms}$ and $I_{J,p,k}^{DL\ inter\ tech\ cells}$ is the total interference power received in the downlink by own terminal k due to terminals and cells of $other$ technologies.

$$I_{J,p,k}^{DL\ inter\ tech} = I_{J,p,k}^{DL\ inter\ tech\ terms} + I_{J,p,k}^{DL\ inter\ tech\ cells} . \tag{230}$$

Note that $I_{J,p,k}^{DL\ inter\ tech}$ is the interference power over the full victim bandwidth W_p . Formulas for DL quantities such as SINR are typically expressed as of a ratio of received EPRE values rather than power levels over the full bandwidth. So $I_{J,p,k}^{DL\ inter\ tech}$ must be transformed to an interfering EPRE for use in those formulas as follows

$$\varepsilon_{J,p,k}^{DL\ inter\ tech} = I_{J,p,k}^{DL\ inter\ tech} / \, W_p \quad . \tag{231}$$

The resulting EPRE can then be included alongside other interfering EPRE values in the SINR formulas. So for example, equation (168) for the DL RS SINR is modified to give

$$(SINR)_{J,p,k}^{DLRS,tx} = \frac{\varepsilon_{J,p}^{DLRS,tx}}{L_{Jk}^{DL}\left(\overline{N}_{p,k}^{DL\ RE} \ + \ I_{J,p,k}^{DLRS,tx} + \varepsilon_{J,p,k}^{DL\ inter\ tech}\right)} \ . \tag{232}$$