# ETSI TR 103 554 V1.1.1 (2018-08)

TECHNICAL REPORT

**Rail Telecommunications (RT);**
**Next Generation Communication System;**
**LTE radio performance simulations and evaluations in rail environment**

Reference
DTR/RT-0047

Keywords
LTE, railways

***ETSI***

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# Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Railway Telecommunications (RT).

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# Executive summary

In order to assess 3GPP LTE radio performance in a rail environment, three scenarios have been defined: Rural, Hilly and Urban, representing various radio conditions typical to rail environment. Each scenario has been defined with its radio parameters, load condition and train speeds.

UIC and E-UIC spectrum bands have been assumed, with bandwidth of 1,4 MHz, 3 MHz and 5 MHz, corresponding to possible deployments with LTE and GSM-R co-existence and deployment with a standalone LTE.

Three different studies are described. One is based on simulation with a software chain tool using a Monte-Carlo statistical approach, including multiple cells in a linear deployment along the track. The two others are based on laboratory radio test bench, featuring hardware communication devices and wireless channel emulators, but not taking into account multiple cells interferences.

The present document includes results from software chain tool study and from one of the two laboratory radio test bench study.

In the present document, only results for LTE using a channel bandwidth of 1,4 MHz with maximum UE power of 23 dBm in the 900 MHz band are provided. A set of initial conclusions has been drawn from these partial results; however a final conclusion will need the completion of the analysis with results for 3 MHz and 5 MHz channel bandwidths and for maximum UE powers of 26 and 31 dBm. Furthermore, the impact of using a TDD mode in other frequency bands will need to be added to the report.

# Introduction

The present document outlines the study conducted within TC RT on LTE radio performance simulations and evaluations in rail environment.

# 1 Scope

3GPP LTE radio access is one candidate for the radio access technology to be used for the Future Rail Mobile Communications System (FRMCS). In the present document, the term FRMCS refers -unless stated otherwise- to the radio part of the communication system.

The present document is intended to:

- Define the simulation parameters relevant to rail environment relating to 3GPP LTE radio performance. This includes in particular operating frequency bands, bandwidths, deployment scenario (inter-site distance), and antenna characteristics, transmit powers and channel models, along with relevant metrics to be evaluated.
- Collect and analyse the simulation results of an LTE system in the rail environment.
- Identify limitations of an LTE system in the rail environment.

Radio performance evaluation of an LTE system could be done by simulation, through software and processing resources only, or through a test bench incorporating pieces of equipment emulating parts of the chain, e.g. the RF. In both cases, it is important to align the parameters and the assumptions made in the simulation and in the evaluation chain to be able to reflect better a deployment in a rail environment, and to better compare and understand the simulation and the evaluation results.

# 2 References

## 2.1 Normative references

Normative references are not applicable in the present document.

## 2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI TS 145 005 (V14.4.0) (04-2018): "Digital cellular telecommunications system (Phase 2+) (GSM); GSM/EDGE Radio transmission and reception (3GPP TS 45.005 version 14.4.0 Release 14)".

[i.2] ETSI TS 136 104 (V14.7.0) (04-2018): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 14.7.0 Release 14)".

[i.3] ETSI TS 136 101 (V14.7.0) (04-2018): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 14.7.0 Release 14)".

[i.4] Recommendation ITU-R M.2135-1 (12-2009): "Guidelines for evaluation of radio interface technologies for IMT advanced".

[i.5] IST-4-027756 Winner II D1.1.2 V1.2 Winner II Part I: "Channel Models", European Commission, Deliverable IST-WINNER D.

[i.6] Ikuno, J. Colom, Martin Wrulich, and Markus Rupp.: "Performance and modelling of LTE H-ARQ." Proc. International ITG Workshop on Smart Antennas (WSA 2009), Berlin, Germany 2009.

[i.7] ETSI TS 136 211 (V14.6.0) (04-2018): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 14.6.0 Release 14)".

[i.8] Recommendation ITU-R M.1225 (1997): "Guidelines for evaluation of radio transmission technologies for IMT-2000".

[i.9] European Integrated Railway Radio Enhanced Network System Requirements Specification, UIC CODE 951, GSM-R Operators Group, December 2015.


# 3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

| | |
|---|---|
| ACS | Adjacent Channel Selectivity |
| AMC | Adaptive Modulation and Coding |
| AWGN | Additive White Gaussian Noise |
| BS | Base Station |
| BTS | Base Transceiver Station |
| BW | Bandwidth |
| CDF | Cumulative Distribution Function |
| CDL | Clustered Delay Line |
| COST | Cooperation of Scientific and Technical |
| CP | Cyclic Prefix |
| DL | Down Link |
| EIRENE | European Integrated Railway radio Enhanced NEtwork |
| eNB | evolved Node B |
| ETU | Extended Typical Urban model |
| E-UTRA | Evolved UMTS Terrestrial Radio Access |
| FDD | Frequency Division Duplex |
| FEC | Forward Error Correction |
| FRMCS | Future Rail Mobile Communications System |
| FSTD | Frequency Switched Transmit Diversity |
| GSM | Global System for Mobile communications |
| GSM-R | Global System for Mobile communication for Railway application |
| HARQ | Hybrid Automatic Repeat-Request |
| HO | Hand Over |
| HST | High Speed Train |
| IMT | International Mobile Telecommunications |
| IP | Internet Protocol |
| ISD | Inter Site Distance |
| ISI | Inter-Symbol Interference |
| ITU-R | Internail Telecommunication Union - Radiocommunication sector |
| LOS | Line Of Sight |
| LTE | Long Term Evolution |
| MAC | Media Access Control |
| MCS | Modulation and Coding Scheme |
| MIMO | Multiple Input, Multiple Output |
| MISO | Multiple Input, Single Output |
| MOS | Mean Opinion Score |
| MRS | Mobile Relay Station |
| NLOS | Non Line Of Sight |
| OFDM | Orthogonal Frequency Division Multiplexing |
| PBCH | Physical Broadcast Channel |
| PDCCH | Physical Downlink Control Channel |
| PDCP | Packet Data Convergence Protocol |
| PDP | Power Delay Profile |
| PER | Packet Error Rate |

| | |
|---|---|
| PHY | PHYsical layer |
| PUCCH | Physical Uplink Control Channel |
| QAM | Quadrature Amplitude Modulation |
| QCI | QoS Class Identifier |
| RB | Resource Block |
| REC | Railways Emergency Call |
| RF | Radio Frequency |
| RLC | Radio Link Control |
| RT | Rail Telecommunications |
| SFBC | Space-Frequency Block Coding |
| SGW | Serving Gateway |
| SIMO | Single Input, Multiple Output |
| SINR | Signal to Interference-plus-Noise Ratio |
| SISO | Single Input, Single Output |
| SNR | Signal to Noise Ratio |
| SRS | System Requirement Specification |
| TC | Technical Committee |
| TCP | Transmission Control Protocol |
| TDD | Time Duplex Division |
| UDP | User Datagram Protocol |
| UE | User Equipment |
| UIC | Union Internationale des Chemins de fer |
| UL | Up Link |
| UMTS | Universal Mobile Telecommunications System |
| USB | Universal Serial Bus |

# 4 Assumptions and parameters for simulations and evaluations

## 4.1 Introduction

In the scope of this study, the following points are addressed:

- Simulations take into account railway specifics
- Simulations are flexible in order to simulate different system configurations, parameter settings and scenarios
- Consideration of different carrier band-widths (at least 1,4, 3 and 5 MHz)
- Consideration of TDD and FDD duplex modes
- Consideration of different subscriber and train densities and distributions
- Considerations of FRMCS system parameters (e.g. Cyclic Prefix)
- Different power classes of FRMCS equipment
- Different antenna radiation patterns and tilts
- SISO, SIMO, MISO und MIMO
- Different installation heights of antennas
- Different distances and densities of fixed transmitter equipment (eNB)
- Different specified and appropriate coding and modulation schemes
- Different 3GPP Releases (e.g. LTE: $\geq$ 13) to take into account new features, e.g. performance improvements for high speed.

## 4.2 Simulation tools

Software simulations are made at radio level, i.e. above the physical layer as depicted in Figure 1. Overheads like pilots and cyclic prefixes are taken in to account, but not the overheads that are added by layers above PHY, in particular PDCP and IP headers.

Other simulations, e.g. hardware simulations and laboratory tests, could have a reference point at application level.

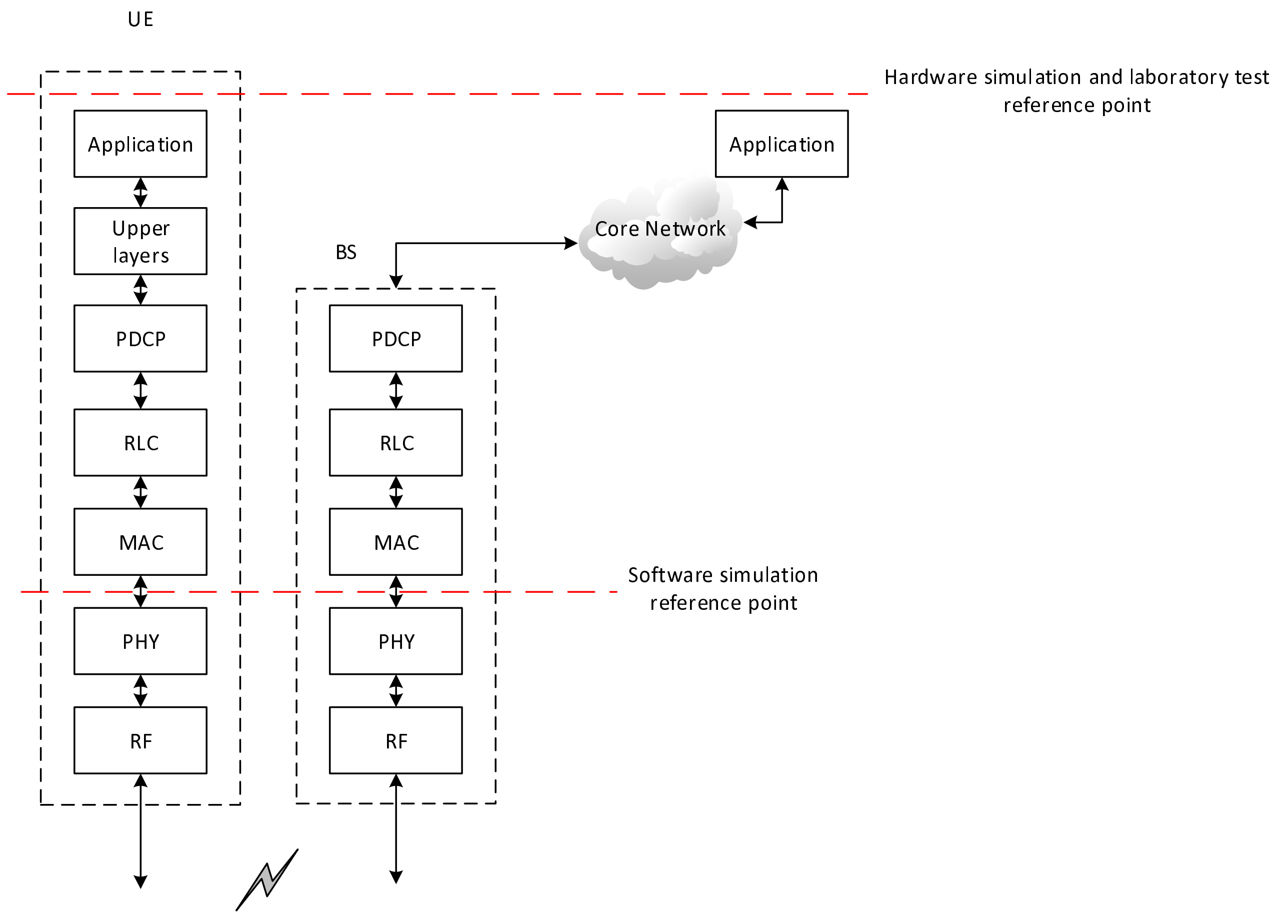



**Figure 1: Reference point for the software simulations**

## 4.3 Scenarios

The objective is to define the minimum number of scenarios which cover the majority of the radio environment.

Three scenarios have been retained: Urban, Rural, and Hilly. Urban is relative to areas where train density is high, but move at moderate speed. Rural scenario typically intends to model high speed lines. Hilly scenario intends to handle more complex situations from radio propagation point of view, with in particular extensive multi-path propagation.

Tunnels are complex scenarios, since they depend widely on tunnel shape and tunnel/train relative geometry. They are not considered in this study as they would require a more long and thorough work.

Only train-ground communications are considered in this study. Handset or shunting area scenarios are for further study.

Whether it is possible to have several antennas on trains roof tops and what could be their characteristic needs further discussions.

# 4.4 Bandwidth and transmit power

## 4.4.1 Bandwidths

Three scenarios are considered, on bandwidths of 1,4 MHz, 3 MHz and 5 MHz in the UIC and E-UIC bands, as depicted in Figure 2:

1) Scenario 1 considers GSM-R in UIC band as per today, with the addition of a 1,4 MHz LTE carrier in the upper part of E-UIC band. This scenario corresponds to a migration phase, with co-existence of both GSM-R and LTE systems.

2) Scenario 2 assumes is an extension of scenario 1 with a LTE carrier extended to 3 MHz in the E-UIC band.

3) Scenario 3 assumes a deployment with no GSM-Rand one LTE 5 MHz carrier in UIC band, overlapping the E-UIC band.

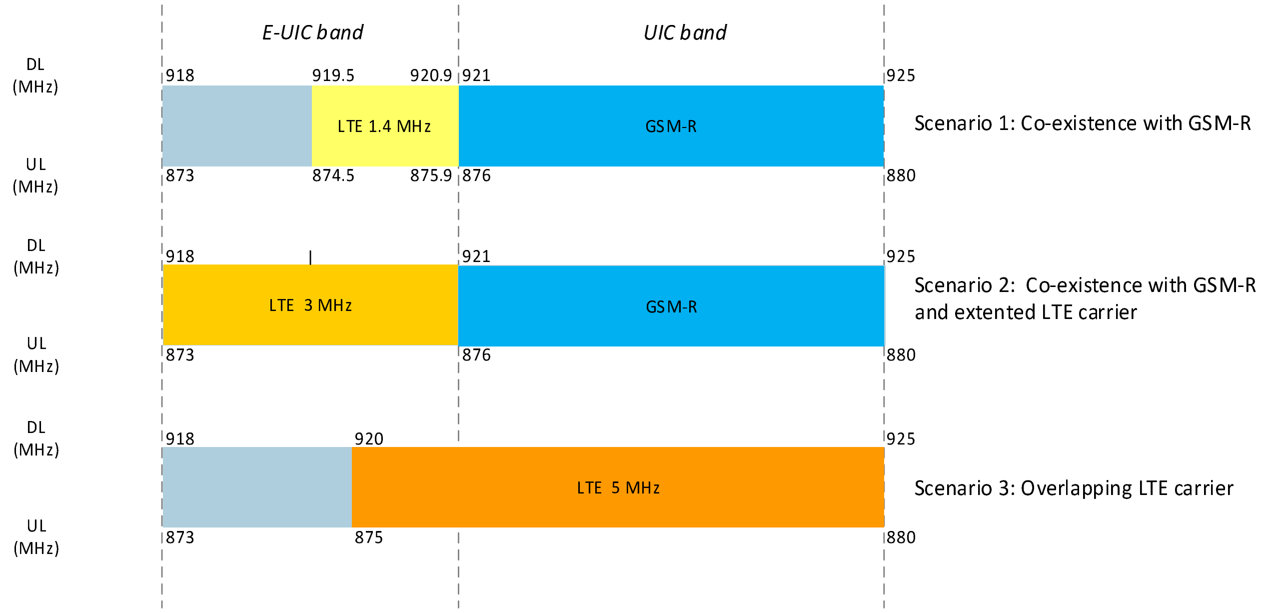



**Figure 2: Carriers and bandwidths in the deployment scenarios considered**

Scenario 1 is of highest priority.

## 4.4.2 Transmit powers

Transmit power in the E-UIC band is subject to limitations in case of FRMCS system deployment uncoordinated with commercial systems operating in neighbouring bands.

The method to compute the maximum transmit power derives the impact from the adjacent channel selectivity related specifications (wideband blocking and narrow band blocking), takes into account applicable effects (0,8 dB desensitization, slope of the filtering, etc.) as well as corrections resulting from spurious emissions from base station transmission and from UE. ACS (Adjacent Channel Selectivity) has been found as not relevant for this study.

Summary of the acceptable maximum transmit power of a FRMCS system in case of uncoordinated deployment is shown in Table 1.

**Table 1: FRMCS acceptable transmitted power at eNB connector taking into account impact of BS Tx spurious emissions and Noise Rise from UE**

| **FRMCS 1,4 MHz channel centre frequency (MHz)** | 918,7 | | | 920,3 | | |
|---|---|---|---|---|---|---|
| **Standard under consideration in adjacent bands** | UMTS | LTE | Multi-Standard | UMTS | LTE | Multi-Standard |
| **FRMCS acceptable Tx power (dBm)** | 24,2 | 22,2 | 22,2 | 48,8 | 45,8 | 48,8 |

In coordinated scenario, the maximum transmit power at 918,7 MHz can be the same than at 920,3 MHz.

# 4.5 Antenna diagrams

## 4.5.1 Antenna diagrams at the base station

Different types of antennas are deployed depending on the area. For the study, two different antennas are selected: One with a horizontal beam angle of 65°, devoted to Non Line Of Sight (NLOS) situations - typically hilly terrains and urban areas, and one more directive, with a horizontal beam angle of 30°, more suited to Line Of Sight (LOS) situations - typically rural areas.

Antenna characteristics are summarized in Table 2 and an extended description is provided in Annex D.

**Table 2: Summary of base station antenna patterns**

| Horizontal Polarization | Vertical Polarization | Gain | Polarization | Usage |
|---|---|---|---|---|
| 65° | 7° | 18 dB | ±45° | NLOS |
| 30° | 8,5° | 20,5 dB | ±45° | LOS/NLOS |

# 4.6 Radio propagation aspects

## 4.6.1 Radio propagation model

Simulations have to be based on railway specific time-variant channel impulse responses of the radio channel in order to take into account multi-path radio propagation and Doppler-effects.

Four families of standards have been considered:

1) Okumura-Hata, Cost 207-GSM, COST 231 models and GSM specified models (see [i.1])

2) ITU-R 1997 for IMT 2000 (see [i.8]) and LTE specified scenarios (see [i.2] and [i.3])

3) ITU-R for IMT advanced (see [i.4])

4) Winner II (see [i.5])

Recent propagation models and multipath profiles have been aimed at being used for wireless systems with a small or medium range. This is coherent since 3G and 4G standards have been developed for capacity rather than for coverage. Early defined models such as COST 207 or 231 were derived at a time when coverage was the main priority rather than high speed operation which is of particular significance within the scope of this study.

Most relevant parameters in rail environment are then:

- Frequency range
- Delays in Cluster Delay Line models
- Geometry, most of models are considering 1,5 m for handheld User Equipment
- Inter Site Distances (ISD)

- LOS scenarios are using Ricean factor with high domination of the direct path

Characteristics of models are summarized in the following Table 3, discrepancies are highlighted in red.

**Table 3: Summary of model characteristics**

| | | Railway current | Okumura-Hata, COST 207-GSM COST 231 | ITU-R IMT 2000 | ITU-R IMT advanced | Winner II |
|---|---|---|---|---|---|---|
| Propagation aspects | Frequency range | Band 8 (900 MHz) | 150 to 1 500 MHz | 2 000 MHz | Rural: 450 MHz to 6 GHz | Rural: 2 GHz to 6 GHz |
| | Inter Site Distance | Up to 12 km | Range up to 100 km | Max = 1 732 m | 20 km for Rural (RMa) (see note) | MRS 1 to 2 km 20 km for Rural (see note) |
| | Path clearance | LOS, Ricean < 3 dB | Ricean Factor = 0 dB air | ETU has no direct path, HST has only direct path | LOS, Ricean factor = 6 dB | LOS, Ricean factor = 6 dB |
| | Delayed paths | Up to 20 µs | HTx: up to 20 µs | Max delay = 5 µs | Max delay = 0,22 µs (not in line with 20 km ISD) | Max delay < 0,5 µs (not in line with 20 km ISD) |
| | Train speed | 360 km/h, projection to 500 km/h | Max = 250 km/h in R 1, no double Doppler | Max = 350 km/h with double Doppler | Max = 350 km/h | Max = 350 km/h |
| Geometry | Base Station Antenna Height | 10 to 45 m | 30 to 200 m | $\Delta hb$ = 0 to 50 m, i.e. up to 46 m for 4 m train antenna height | Up to 35 m | 20 to 70 m |
| | Train Antenna Height | 4 m to 4,5 m | 1 to 10 m | | 1,5 m | 1,5 m / 2,5 m |
| NOTE: Delays are shorter than what can be expected with such ISD. | | | | | | |

Indeed, propagation and geometry parameters that are deemed particularly relevant for Railways are summarized below.

**Table 4: Main characteristics of Railway context**

| | | |
|---|---|---|
| **Propagation aspects** | Frequency range | Band 8 (900 MHz) |
| | Inter Site Distance | Up to 12 km |
| | Path clearance | LOS, Ricean < 3 dB |
| | Delayed paths | Up to 20 µs |
| | Train speed | 360 km/h, projection 500 km/h |
| **Geometry** | Base Station Antenna Height | 10 m to 45 m |
| | Train Antenna Height | 4 m to 4,5 m |

The Ricean factor taken here corresponds to worst case scenario. In actual deployments, higher values could be encountered, leading to more favourable channel conditions.

## 4.6.2 Conclusion

Okumura-Hata models and COST 207-GSM COST 231 family (see [i.1]) are taken as the basis.

## 4.7 Frequency reuse scheme

In LTE radio, the frequency band is split in Resource Blocks (RB) which can be allocated individually to UEs by the base station scheduler for each frame. All LTE cells may operate on the same frequency band; however, to mitigate interference from neighbouring LTE cells, one technique is to coordinate RB allocations among cells. One possible coordination scheme is fractional frequency reuse, which consists for example in allocating different RBs among two neighbouring cells to cell edge UEs, while still allocating all the RBs (at a reduced power) for cell centre UEs (see Figure 3). This can be seen as a frequency reuse factor 1 for cell centre UEs, and a frequency reuse factor > 1 (equal to 2 in Figure 3 example) for cell edge UEs. Hence, not all RBs are allocated to cell edge UEs, but this is compensated by a better SINR for those blocks.

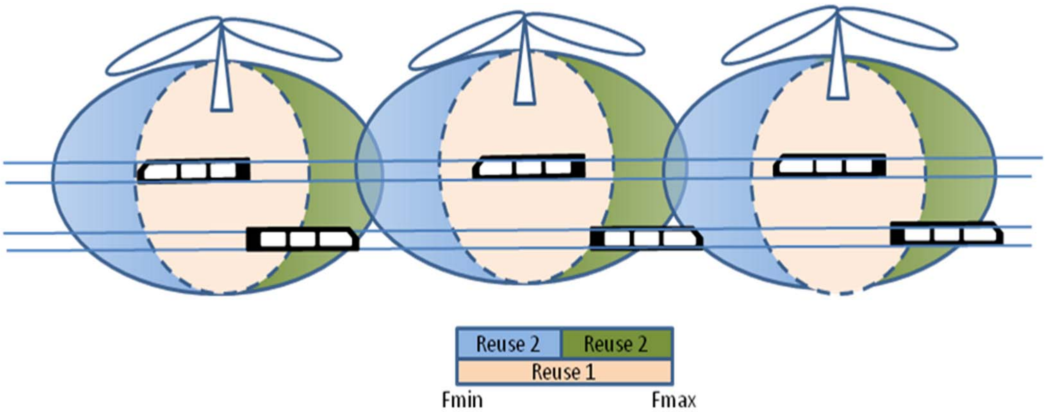



**Figure 3: Example of fractional frequency reuse for rail deployment**

Results should indicate which kind of Fractional Frequency Reuse techniques is used.

## 4.8 Summary

Table 5 sums up all the parameters.

**Table 5: Summary of evaluation parameters**

| Environment/scenario | Rural/Urban |
|---|---|
| Railway shape and LOS/NLOS propagation | Rural:<br>Straight: LOS<br>Curves: NLOS<br>(2 separate sets of results)<br>Hilly:<br>NLOS only<br>Urban:<br>NLOS only |
| Carrier Frequency (DL/UL) (MHz) | 875,2/920,2 (for 1,4 MHz bandwidth)<br>874,5/919,5 (for 3 MHz bandwidth)<br>877,5/922,5 (for 5 MHz bandwidth) |
| Bandwidth (MHz) | 1,4 (mandatory)<br>3 (optional)<br>5 (optional) |
| Inter-site distance (ISD) (km) | Rural: 8<br>Urban: 2 and 4 |
| BS antenna height (m) | 18 (urban) - 30 (rural) |
| Train antenna height (m) | 4,5 |
| Tower to track distance (m) | 15 |
| Neighbour cells load | **Rural:** 4 trains (2 in each direction)<br>**High speed:** 2 trains (1 in each direction)<br>**Urban:**<br>- 6 trains (3 in each direction)<br>- 4 trains (2 in each direction)<br>See note 1 |

| Environment/scenario | Rural/Urban |
|---|---|
| Train speeds (km/h) | **Urban:** 80<br>**Rural:** 350<br>**Hilly:** 160 |
| DL max power (dBm) | In UIC-band:<br>46 before feeder (output of the BTS)<br>3 dB feeder loss<br>In E-UIC band (see clause 4.4.2)<br>22 or 46 (output of the BTS)<br>3 dB feeder loss |
| UL max Power (dBm) | 23<br>26<br>31<br>See note 2 |
| UL Power Control | For instance: Open loop full compensation to be mentioned along with the results. |
| Channel Estimation | For instance: Real channel estimation - Frequency-domain Wiener 1-D - Time interpolation - to be mentioned along with the results. |
| Link Channel Model<br>Tap delay lines<br><br><br>Clustered delay lines | <br>Based on ETSI TS 145 005 [i.1]<br>Urban area 6 taps<br>Rural area 6 taps<br>Hilly terrain 12 taps<br>*Channels for different antennas are not correlated*.<br><br>ETSI TS 145 005 [i.1] channel models are Tapped Delay Line models. Other Models (Recommendation ITU-R M.2135-1 [i.4]) provide additional small scale parameters (Angles of arrival/departure (AoA/AoD) of the rays). To take into account some small scales parameters, ETSI TS 145 005 [i.1] channel models can be combined with the AoA/AoD provided in ITU-R models. Since the number of taps in ETSI TS 145 005 [i.1] models (6 taps/12 taps) is generally different from ITU-R models, AoA/AoD from ITU-R models corresponding to the strongest first 6/12 taps are considered for this hybrid channel model. |
| Path Loss Model (propagation model) | **Urban:** Okumura-Hata<br>(LOS/NLOS effect is only taken into account in link channel model through Rice coefficient distribution for the first tap)<br>**Rural:** Hata sub-urban<br>(LOS/NLOS effect is only taken into account in link channel model through Rice coefficient distribution for the first tap)<br>**Hilly:** Hata sub-urban |
| Shadowing standard deviation (dB) | **Urban:** Okumura-Hata<br>8 dB (NLOS only)<br>**Rural:** Hata sub-urban<br>6 dB in LOS, 8 dB in NLOS<br>**Hilly:** 8 dB (NLOS only) |
| Noise (dBm) | -121,4<br>See note 3 |
| Cyclic prefix | **Rural:** Extended prefix<br>**Urban:** Normal prefix<br>**Hilly:** Extended prefix |
| Fractional frequency reuse technique | *To be mentioned along with the results.* |
| Antenna pattern eNB/Antenna gain | See clause 4.5.1<br>See note 4 |
| eNB antenna downtilt (°) | *To be mentioned along with the results.* |
| Antenna pattern UE/antenna gain | One antenna: Omnidirectional/0dBi - Vertical polarization<br>Two antennas: Vertical polarization, > 10λ separation<br>See note 5 |
| MIMO schemes | DL: 2x1, 4x1<br>DL: 2x2, 4x2<br>UL: 1x2, 1x4 |
| NOTE 1: The aggregate data traffic per cell is 100 %.<br>NOTE 2: It is considered that the UE antenna gain compensates the feeder loss.<br>NOTE 3: Corresponds to thermal noise in a Resource Block of 180 kHz.<br>NOTE 4: In rural environment with straight line railway shape, the 30° HP antenna is assumed.<br>NOTE 5: For the antenna gain, see note of 'UL max Power' parameter. | |

## 4.9 Outcomes of the simulations

Output metrics need to include at least throughputs for DL and UL under the following conditions:

- Peak Data Rate
- Average
- 5 %-tile cell edge. This metric corresponds to the worst case of radio propagation conditions at the worst position in the cell (maximum throughput experienced by the 5 % of trains with worst throughput)

NOTE: This 5 %-tile cell edge (or *Worst Cell Edge)* differs from coverage specification as defined in EIRENE SRS ([i.9]), in which the specified GSM-R radio coverage probability is 95 % in each location intervals of 100 m.

Worst cell edge is 5 %-tile on every location starting from the hand over point, and therefore the associated data throughput corresponds to a much more severe criteria than the one used in EIRENE specification ([i.9]).

# 5 Simulation results

## 5.1 Results set 1

### 5.1.1 Description

The simulator used for this result set is a software chain tool using a Monte-Carlo statistical approach. It simulates a complete LTE PHY layer, i.e. it operates at '*Software simulation reference point*' as defined in Figure 1.

The simulator considers multiple cells in a linear deployment along the track and encompasses link-level simulation as well as system-level simulation.

Link level simulations allow to compute the bit error rate and packet/block error rate (PER) of the radio transmission scheme, including detailed simulation of modulation and coding, MIMO scheme, channel estimation, small-scale fading effects and AWGN. However, link level simulation does not include any effect of large-scale fading, i.e. distance-dependent path-loss and shadowing, which impacts the (experienced) Signal-to-Noise Ratio (SNR) as well as the inter-cell interference level.

System level simulations are required in order to quantify the impact of inter-cell interference on the system throughput at cell level.

The simulation tool comprises then:

**Step 1: Link level simulation**

1) Computation of the $PER_i$ vs. Signal-to-Interference-plus-Noise Ratio (SINR) for $N$ different transmission schemes (characterized by a specific modulation, coding rate, and MIMO scheme) that results in link level throughputs $T_i$, $i=1,\ldots,N$ (assuming AWGN interference).

2) For each transmission scheme $i$ and each SINR value, computation of the resulting throughput $T_{res,i}(SINR)$ taking into account PER as

$$T_{res,i} = T_i \times \left(1 - PER_i\left(SINR\right)\right)$$

3) For each SINR, storage in a look-up table of the maximum resulting throughput as shown in Figure 4 among all transmission schemes (modulation, coding rate, MIMO) as a result of ideal link adaptation to large-scale channel properties:

$$T_{\max}\left(SINR\right) = \arg\max_{i}\left(T_{res,i}\left(SINR\right)\right)$$

**Step 2: System level simulation**

1) For many drops of User Equipments (UEs) and many large-scale channel realizations (including large-scale fading statistics), computation of the resulting SINR for each UE:

- A drop is a realization of UE positions within the cells. These positions are randomly drawn under the constraints of the scenario of interest. For instance, the UE distribution depends on UE density.

2) From all the drops, computation of the Cumulative Density Function (CDF) of the throughput by using the obtained SINR values as inputs in the look-up table $T_{\max}(SINR)$ obtained in the link-level evaluation step.

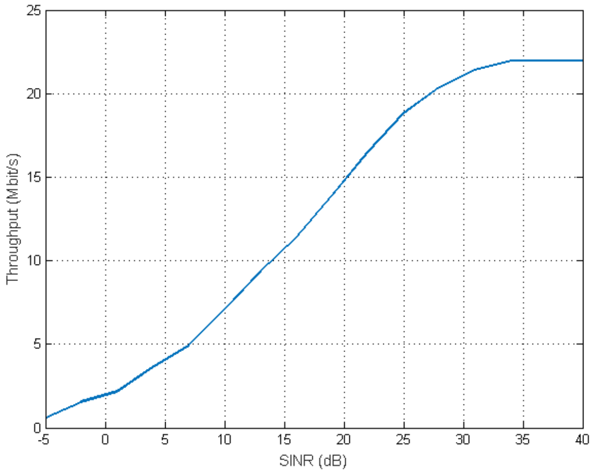



**Figure 4: Maximum resulting throughput example for a given transmission scheme and UE speed (link level simulation)**

Antenna patterns are taken into account together with antenna down-tilt in the system level step. Large-scale fading statistics follows a log-normal distribution.

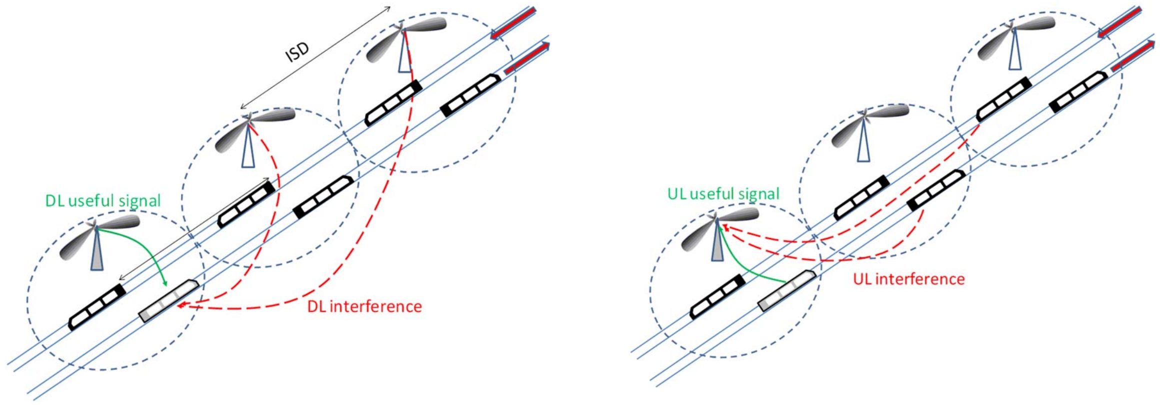
In this railway environment, a straight railway line is assumed, with trains moving on both directions (see Figure 5). The Inter Site Distance (ISD) is set depending on the scenario, i.e. ISD is set to 8 km for rural and to 2 km for urban, as required in clause 4.8.

Each train embeds one UE and train positions are drawn following a uniform random distribution ensuring the train density requirement for each scenario, i.e. 1 train per cell in each direction in high velocity train scenario, 2 in rural scenario and 3 in urban scenario. These train positions form a train position set, each set corresponding to a UE drop.

A worst-case interference level is assumed: all active cells are fully loaded in both UL and DL, i.e. transmission occurs over the whole bandwidth. DL interference experienced by the train in the serving cell depends on its position. UL interference in the serving cell depends on the position of the trains in neighbour cells.

In total, 1 600 train positions sets have been considered during simulations, with 400 channel models realizations per set.

From system-level simulations, the cell average spectral efficiency and the cell-edge throughput (e.g. the 5 %-tile throughput) are computed. For getting the 5 %-tile throughput, the throughput CDF at any position of a track is computed. This is different from the cell-edge throughput computed in 3GPP, which is the cell 5 %-tile throughput taken over the entire cell coverage. The resulting curve allows evaluating the 5 %-tile data throughput at the worst position of the train on the track.




(a) (b)

**Figure 5: Railway line configuration and inter-cell interference (a: downlink; b: uplink)**

## 5.1.2 Specific assumptions and parameters

- Link channel model: As foreseen in clause 4.7, link level simulations combine Power Delay Profiles (PDP) taken from ETSI TS 145 005 [i.1] and geometrical aspects (angle of arrival and angle of departure of the rays) of Clustered Delay Lines (CDL) from Recommendation ITU-R M.2135-1 [i.4].
- Channel estimation includes a time-interpolation between consecutive subframes. It introduces a small processing delay (0,07 ms in downlink with 2 transmit antennas, 0,14 ms with 4 transmit antennas and 0,29 ms in uplink) but lowers Doppler effect.
- In DL, the MIMO schemes that have been chosen for the simulations are transmission schemes providing transmit diversity (see clause 6.3.4.3 of ETSI TS 136 211 [i.7]), as they are more robust to the high train velocity:
  - The transmit diversity scheme with two transmit antennas is the Alamouti Space Frequency Block Code (SFBC) applied on two adjacent sub-carriers (spatial diversity of $2\ N_R$ with $N_R$ number of receive antennas).
  - The transmit diversity scheme with four transmit antennas is a combination of Alamouti SFBC and Frequency Switched Transmit Diversity (FSTD) on four adjacent sub-carriers (spatial diversity of $4\ N_R$).
- In UL, single-antenna transmission only is considered (SIMO) (diversity gain of $N_R$).
- Transmit power in DL is 43 dBm taking into account a 3dB feeder loss.
- Transmit power in UL is 23 dBm.
- Antenna tilt is 3 degrees downtilt, if not stated otherwise.
- Bandwidth is 1,4 MHz, centred at 875,2/920,2 MHz.
- Rice factor for rural model (high speed scenario) is 0,4475 dB. There is no line of sight component in the other models.
- Large scale shadowing standard deviation is 4 dB in Rural model, and 8 dB for Urban and Hilly models.

**Frequency reuse scheme**

The simulations do not implement a fractional frequency reuse algorithm. Separate results are provided for different frequency reuse factors (hard frequency reuse), leading to a strong decrease of offered throughput in cell centres for frequency reuse > 1.

However, with a fractional frequency reuse algorithm, the throughput results with frequency reuse 2 or 3 will be the ones cell edge UEs could experience, while frequency reuse 1 results should be considered for cell centre UEs.

### 5.1.3 Results

Simulations have been made for the different scenarios foreseen in clause 4 and considering frequency reuse factors of 1, 2 and 3.

The different scenarios simulated are the following.

**Table 6: Scenarios summary**

| Scenario name | Model and speed | ISD (km) | Neighbour cell load (trains) |
|---|---|---|---|
| Urban | Urban (NLOS, 80 km/h) | 2 | 6 |
| High Density | Urban (NLOS, 80 km/h) | 4 | 4 |
| Hilly | Hilly (NLOS, 160 km/h) | 8 | 2 |
| High speed | Rural (LOS, 350 km) | 8 | 2 |

A summary of the throughput performance is provided in this clause. In the summary tables:

- *Cell Centre* column corresponds to the maximum throughput available at the cell centre. It is the maximum data throughput that can be expected in a cell for the scenario considered and corresponds to the *Peak Data Rate* defined in clause 4.9;
- *Median cell edge* corresponds to the 50 %-tile value at the worst position in the cell; and
- *Worst cell edge* to the 5 %-tile value at the worst position in the cell (see clause 4.9).

UL and DL throughput values correspond to the total throughputs available in the cell, to be shared among the different trains that are served by the base station.

**High speed scenario**

| | | | Throughput (Mbit/s) | | | | | | Throughput (Mbit/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed (km/h) | DL | Reuse factor | Cell centre | Median cell edge | Worst cell edge | Speed (km/h) | UL | Reuse factor | Cell centre | Median cell edge | Worst cell edge |
| 350 | 2x2 | 1 | 3,50 | 0,30 | 0 | 350 | 1x2 | 1 | 3,60 | 0,25 | 0 |
| 350 | 4x2 | 1 | 3,50 | 0,40 | 0 | 350 | 1x4 | 1 | 3,60 | 0,40 | 0 |
| 350 | 2x2 | 2 | 1,75 | 1,00 | 0,45 | 350 | 1x2 | 2 | 1,80 | 0,75 | 0,30 |
| 350 | 4x2 | 2 | 1,75 | 1,20 | 0,45 | 350 | 1x4 | 2 | 1,80 | 1,0 | 0,50 |
| 350 | 2x2 | 3 | 1,20 | 1,20 | 0,50 | 350 | 1x2 | 3 | 1,20 | 0,70 | 0,40 |
| 350 | 4x2 | 3 | 1,20 | 1,10 | 0,60 | 350 | 1x4 | 3 | 1,20 | 0,80 | 0,60 |

**Urban scenario**

| | | | Throughput (Mbit/s) | | | | | | Throughput (Mbit/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed (km/h) | DL | Reuse factor | Cell centre | Median cell edge | Worst cell edge | Speed (km/h) | UL | Reuse factor | Cell centre | Median cell edge | Worst cell edge |
| 80 | 2x2 | 1 | 4,20 | 0,40 | 0 | 80 | 1x2 | 1 | 4,40 | 0 | 0 |
| 80 | 4x2 | 1 | 4,00 | 0,40 | 0 | 80 | 1x4 | 1 | 4,40 | 0 | 0 |
| 80 | 2x2 | 2 | 2,20 | 1,12 | 0,10 | 80 | 1x2 | 2 | 2,20 | 0,30 | 0 |
| 80 | 4x2 | 2 | 2,00 | 1,25 | 0,10 | 80 | 1x4 | 2 | 2,20 | 0,55 | 0 |
| 80 | 2x2 | 3 | 1,40 | 1,25 | 0,30 | 80 | 1x2 | 3 | 1,45 | 0,45 | 0 |
| 80 | 4x2 | 3 | 1,30 | 1,15 | 0,30 | 80 | 1x4 | 3 | 1,45 | 0,75 | 0,05 |

**High density scenario**

| | | | Throughput (Mbit/s) | | | | | | Throughput (Mbit/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed (km/h) | DL | Reuse factor | Cell centre | Median cell edge | Worst cell edge | Speed (km/h) | UL | Reuse factor | Cell centre | Median cell edge | Worst cell edge |
| 80 | 2x2 | 1 | 4,20 | 0,30 | 0 | 80 | 1x2 | 1 | 4,30 | 0 | 0 |
| 80 | 4x2 | 1 | 4,00 | 0,40 | 0 | 80 | 1x4 | 1 | 4,30 | 0 | 0 |
| 80 | 2x2 | 2 | 2,10 | 1,25 | 0,10 | 80 | 1x2 | 2 | 2,20 | 0,30 | 0 |
| 80 | 4x2 | 2 | 2,00 | 1,25 | 0,15 | 80 | 1x4 | 2 | 2,20 | 0,50 | 0 |
| 80 | 2x2 | 3 | 1,40 | 1,25 | 0,4 | 80 | 1x2 | 3 | 1,45 | 0,45 | 0 |
| 80 | 4x2 | 3 | 1,30 | 1,12 | 0,30 | 80 | 1x4 | 3 | 1,5 | 0,75 | 0,1 |

**Hilly scenario**

| | | | Throughput (Mbit/s) | | | | | | Throughput (Mbit/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed (km/h) | DL | Reuse factor | Cell centre | Median cell edge | Worst cell edge | Speed (km/h) | UL | Reuse factor | Cell centre | Median cell edge | Worst cell edge |
| 160 | 2x2 | 1 | 2,10 | 0,25 | 0 | 160 | 1x2 | 1 | 3,60 | 0,25 | 0 |
| 160 | 4x2 | 1 | 2,40 | 0,35 | 0 | 160 | 1x4 | 1 | 3,60 | 0,50 | 0 |
| 160 | 2x2 | 2 | 1,00 | 0,90 | 0,15 | 160 | 1x2 | 2 | 1,80 | 0,75 | 0,15 |
| 160 | 4x2 | 2 | 1,20 | 1,10 | 0,13 | 160 | 1x4 | 2 | 1,80 | 1,13 | 0,25 |
| 160 | 2x2 | 3 | 0,70 | 0,70 | 0,25 | 160 | 1x2 | 3 | 1,20 | 0,40 | 0,20 |
| 160 | 4x2 | 3 | 0,85 | 0,80 | 0,30 | 160 | 1x4 | 3 | 1,20 | 1,0 | 0,3 |

Figures in the summary tables are picked up from (throughput vs. distance to base station) curves. An example of such a curve is provided in Figure 6; the full set can be found in Annex B.

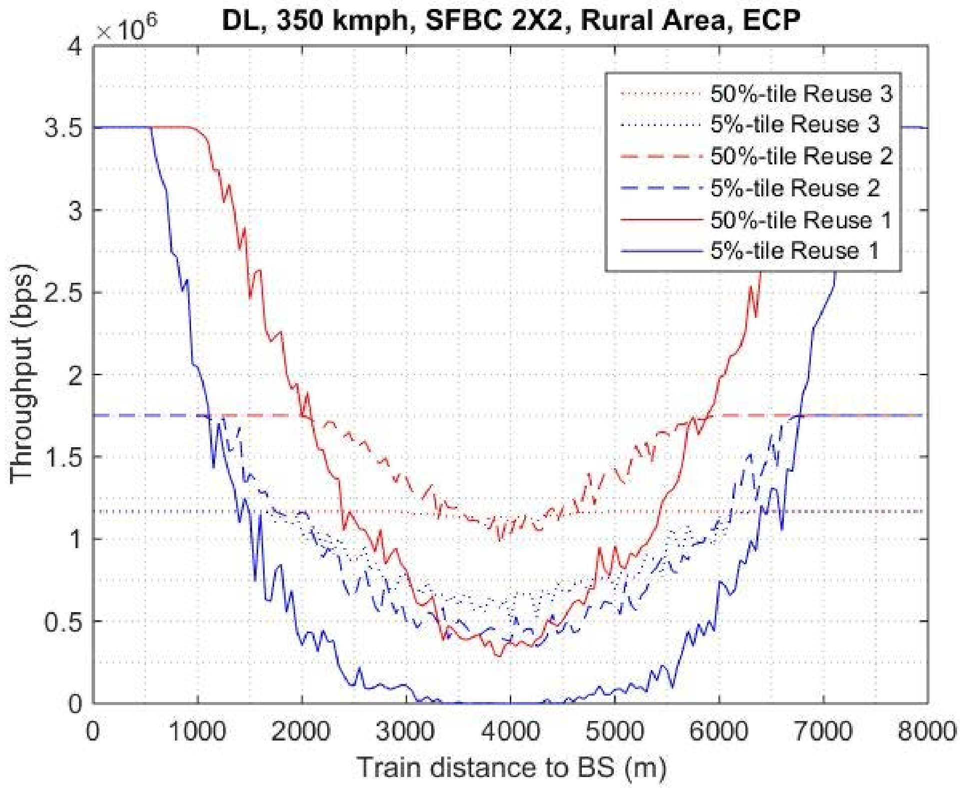



**Figure 6: Example of throughput vs distance to base station**

### 5.1.4 Notes and remarks

**Interference from neighbouring cells**

Interference from neighbouring cells explains the low performance obtained for *worst cell edge* metric. Indeed, neighbouring cells are assumed to have a 100 % cell load, which is a pessimistic assumption. The impact on Urban scenario throughput performance is particularly visible, due to a smaller cell size compared to other scenarios. Antenna tilt and interference mitigation techniques should greatly improve the results.

**Antenna tilt**

An antenna down tilt of 3 degrees has been taken for all scenarios. However, in Urban scenarios, an antenna tilt of 5 degrees may provide better throughput at cell edge for frequency reuse 2 and 3 patterns, as shown in Table 7.

**Table 7: UL Throughput for Urban scenario with an antenna tilt of 5°**

| | | | Throughput (Mbit/s) | | |
|---|---|---|---|---|---|
| **Speed (km/h)** | **UL** | **Reuse factor** | **Cell centre** | **Median cell edge** | **Worst cell edge** |
| 80 | 1x2 | 2 | 2,20 | 0,70 | 0,05 |
| 80 | 1x4 | 2 | 2,20 | 1,13 | 0,10 |
| 80 | 1x2 | 3 | 1,40 | 0,80 | 0,15 |
| 80 | 1x4 | 3 | 1,40 | 1,25 | 0,25 |

**Shadowing**

The large scale shadowing is simulated with a log-normal distribution having a standard deviation of 4 dB in Rural model, and 8 dB for Urban and Hilly models. In the 5 %-tile curves, this may correspond to shadowing values that can reach 8 dB (Rural) and 16 dB (Urban and Hilly).

**Doppler impact**

Under the assumptions of this study, Doppler has not a big impact on throughput performances compared to other factors as interferences, neither in UL nor in DL. This is due to the relative low frequency band, and the inclusion in the channel estimation at receiver side of a time-interpolation between consecutive subframes.

**Uplink vs. downlink performances**

It can be noticed that uplink and downlink throughputs are almost the same for rural and urban deployments. For hilly, the uplink throughput is even much higher than the downlink throughput.

Indeed, interferences in DL are in average higher than interferences in UL, due to less transmit power in UL compared to DL and due to the varying position on the interfering trains.

Moreover, UL MIMO scheme strongly relies on receive diversity: Having 4 antennas in reception (e.g. UL in 1x4) provides a SINR gain of 3dB compared to having 2 antennas in reception (all DL schemes). In addition, Reference Signals (pilot patterns) have higher density in UL than in DL, leading to have an UL channel estimation more robust for high MCS.

For hilly, the channel is characterized by a very high frequency selectivity (the max delay spread is 20µs, which is higher than the length of the extended cyclic prefix with a coherence bandwidth of 50 KHz). UL channel estimation is more robust than in DL in these conditions: In UL, the 64 QAM can be used at cell centre, which is no longer the case for the DL of hilly terrain channel.

## 5.2 Results set 2

### 5.2.1 Description

#### 5.2.1.1 Lab setup high level description

A system level simulation is proposed based on an RF lab with eNodeBs in band 8 or band 20. Advantage of RF lab based approach is that all cell topology methods (i.e. CoMP, MIMO) can be implemented as part of the simulation. It operates at '*Hardware simulation and laboratory test reference point*' as defined in Figure 1.

Lab setup includes (see Figure 7):

- 2 eNodeBs in a band neighbouring the E-GSM-R band (band 8 or band 20)
- Fixed attenuators RF cable wired to the output of each eNodeB
- 3GPP Channel Fading Simulator wired to the fixed attenuators to insert the fading
- On-board LTE modem RF cable wired to the 3GPP Channel Fading Simulator
- Traffic Generator/Analyser port connected to IP port of the On-board LTE modem
- Service Gateway connected to each eNodeB via IP connection
- Traffic Generator/Analyser port connected to IP port of Serving Gateway

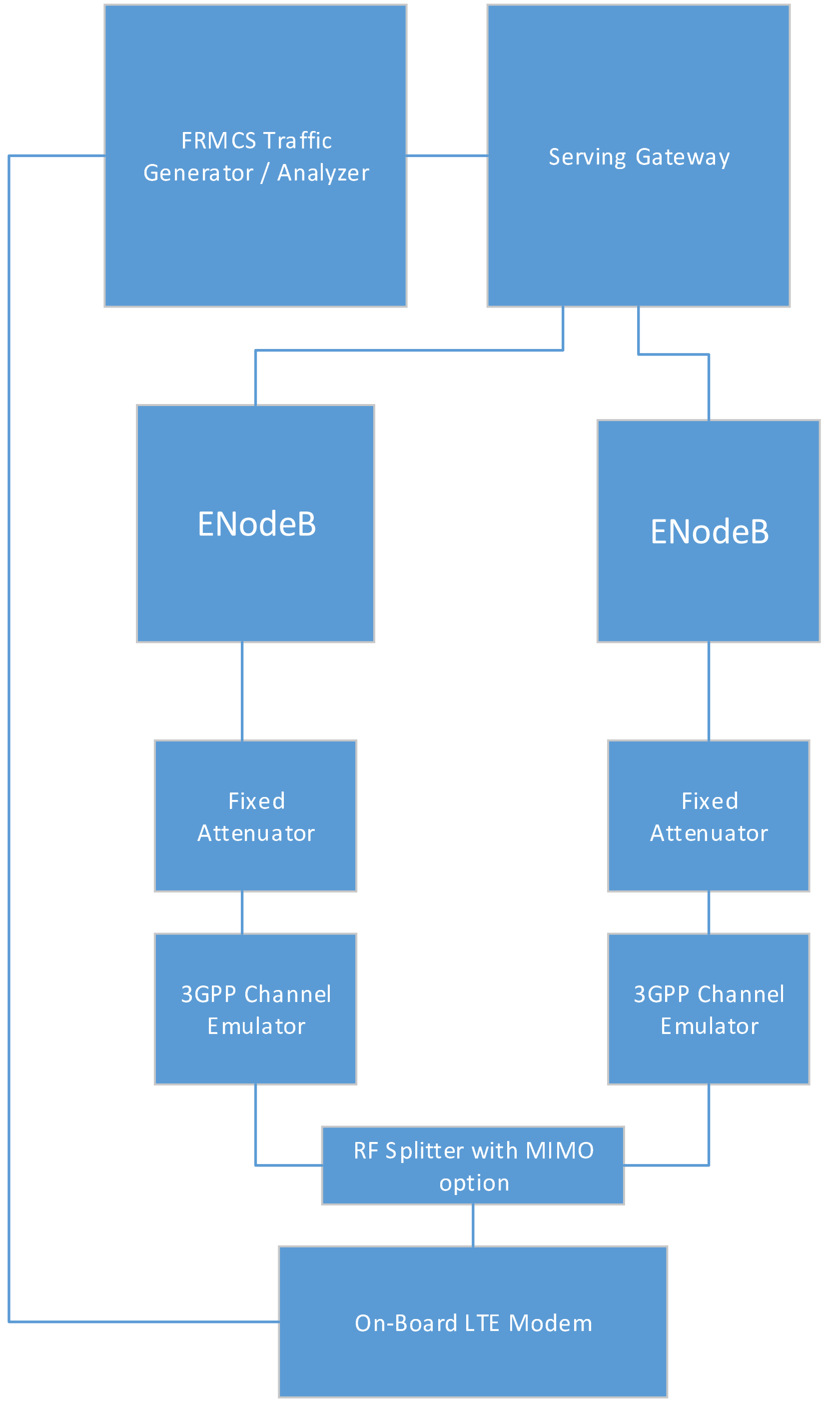



**Figure 7: Architectural diagram of the Lab Simulation Setup**

#### 5.2.1.2 Lab setup: 3GPP RF Channel Emulator

Fading Profiles Available: Constant, Rayleigh, Rice, Nakagami, Lognormal, Suzuki, Pure Doppler, flat, rounded, Gaussian, Jakes, Butterworth, user-defined profiles, models from 3rd party simulation tools and ray-tracing applications.

Channel Configuration Topologies: Single or multiple independent or fully synchronized MIMO, MISO, SIMO, SISO, CoMP and relaying transmission schemes.

Run-time fading engine Amplitude, delay, Doppler and environment separately controlled for each fading channel.

Emulation of 2D and 3D beamforming channels, single and multi-user scenarios.

Emulation of high speed train scenarios, measured with channel sounder or defined with channel modelling tools.

Geometric channel modelling tool for user-defined Multi-link MIMO, beamforming and smart antenna testing; includes dynamic spatial, defined antenna patterns.

#### 5.2.1.3 Lab setup: FRMCS Traffic Generator and Analyzer

Multi-FRMCS Application emulation provides end-to-end measurements from ingress/egress of SGW to the ingress/egress of the UE per application or bearer. Data emulation supports voice, video, and data traffic generation. Dedicated radio bearers are established from the test system and the service type is appropriately mapped to the correct bearer. By fully-loading the lab environment with enough traffic to cause congestion and resource contention of the RF interface it is possible to determine the maximum throughput per bearer, per UE and per channel.

By setting traffic generator to configure layer 7 (L7) activities it is possible to emulate FRMCS application activities according to specific QCIs and DSCPs. The traffic analyser then measures QCI performance for each of the L7 activities.

KPIs for FRMCS applications include:

- Loss packets
- Max and average jitter
- Average latency
- Mean Opinion Score (MOS)
- Throughput

**QoS Validation**

It is possible using this setup to measure the performance of the network while varying input loads, such as traffic rates and types, and subscriber classes. In this way one can vary specific FRMCS activities and measure the QoS impact on the others. One of the railway's important tests is the verification of latency thresholds that ensure delay-sensitive train control and REC traffic gets priority over best-effort data traffic. The railway can use the traffic generator equipment to emulate a constant level of data traffic (number of subscribers and data rate), while increasing the level of emulated train control or REC traffic.

### 5.2.2 Specific assumptions and parameters

No specific parameters and assumptions have been considered. See clause 4.7.

### 5.2.3 Results

No results available from this set.

### 5.2.4 Notes and remarks

No results available from this set.

## 5.3 Results set 3

### 5.3.1 Description

The primary objective of the study for this result set is to assess the uplink throughput performance of a LTE based radio setup when used in a Railways environment.

For that purpose, measurements have been carried out under conditions as close as possible to "real life" railways situation.

An evolved radio test bench, including a wireless channel emulator, has been customized to reflect the most critical railways and high-speed propagation conditions.

Extra features have been implemented to manually select the Modulation Coding Scheme (MCS) and measure throughput for each of them.

The test set-up is represented in Figure 8.

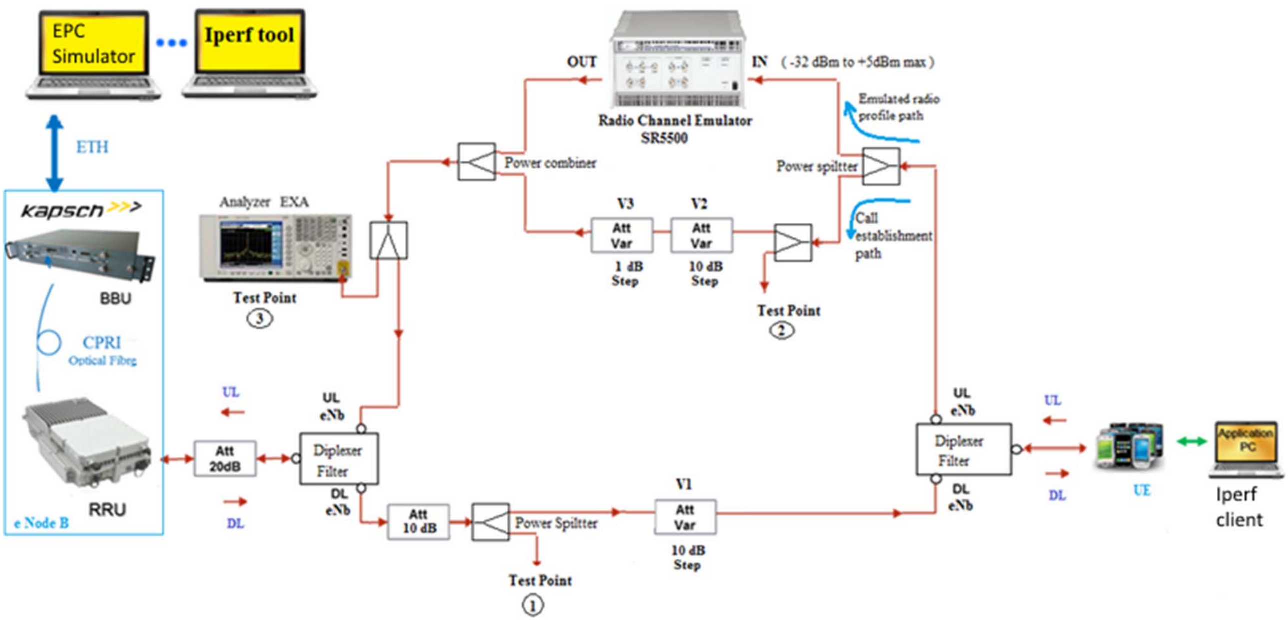



**Figure 8: Measurement setup schematic**

Data throughput evaluation (UDP throughput using 1 024 bytes packet size.) was assessed with widely-used Iperf network performance measurement and tuning tool (see https://iperf.fr/). Every throughput value provided in clause 5.3.3 is the average of at least one hundred fluctuating values over a period of time of at least 100 s. Iperf is delivering 1 throughput value per second. Reported results are about effective payload.

Multipath are simulated with a Spirent Radio Channel Emulator SR 5500. This device is able to add white Gaussian noise to generate desired SNR level.

## 5.3.2 Specific assumptions and parameters

Parameters for these experiments have been selected as close as possible to recommendations. Exceptions or complementary information are listed below:

- Mobile handset is a category 3 USB dongle:
  - Maximum constellation is 16 QAM.
- Network loading is 1 user.
- Normal Cyclic Prefix.
- Configuration under test is 1 x 1, however an extrapolation is performed to evaluate 1 x 2 (receive diversity at eNB level).
- Down Link path is not experiencing multi-path effects.
- Multipath scenario is derived from ETSI TS 145 005 [i.1]:
  - Hilly terrain profile is used, however profile is restricted to 6 taps.

- Considered Doppler shift is higher than the one resulting from the speed, it is incorporating some double effect part (Shift is doubled), applied shifts are:
    - 360 km/h: 600 Hz (named HT600)
    - 500 km/h: 834 Hz (named HT834)

- Speeds are: 360 km/h and 500 km/h for 3 MHz LTE Channel BW, and 360 km/h for LTE 1,4 MHz Ch BW.

A simplified link budget has been made to evaluate worst case SNR (at Hand Over point: HO) and extract minimum guaranteed data throughput along the track. SNR are given for two antenna gain (17 dBi and 21 dBi) and extrapolation are given to evaluate performance with 2 way Rx diversity at Base Station level.

**Table 8: Simplified link budget at HO point**

| UL link budget (1x1) | | | |
|---|---|---|---|
| Train parameters | UE Tx power (dBm) | 23 | |
| | Coupling loss (dB) | 2 | |
| | Antenna gain (dB) | 2 | |
| | EIRP (dBm) | 23 | |
| | Height (m) | 4 | |
| Base station | Antenna gain (dB) | 17 | 21 |
| | Height (m) | 40 | |
| | Coupling loss (dB) | 3 | |
| | eNB NF (dB) | 3 | |
| Path loss (BS 40 m, MS 4m) | Distance (km) | 4 | |
| | Path loss (dB) | 129 | |
| | Standard deviation (dB) | 8 | |
| | Margin for 95% (dB) | 13,2 | |
| | Guaranteed (dB) | 142,2 | |
| | UL Rx lev (dBm) | -105,2 | -101,2 |
| LTE 1,4 MHz | Thermal noise (dBm) | -113,7 | |
| | Noise floor (dBm) | -110,7 | |
| | SNR (dB) | **5,5** | **9,5** |
| | Rx Div min gain (dB) | 3,0 | |
| | SNR with Rx Div (dB) | 8,5 | 12,5 |
| LTE 3 MHz | Thermal noise (dBm) | -110,0 | |
| | Noise floor (dBm) | -107,0 | |
| | SNR (dB) | **1,8** | **5,8** |
| | Rx Div min gain (dB) | 3,0 | |
| | SNR with Rx Div (dB) | 4,8 | 8,8 |

## 5.3.3 Results

In this clause, only LTE 1,4 MHz channel BW with 360 km/h is considered, other results are placed in Annex C. Results are reported and SNR conditions at HO point are superimposed to derive corresponding data rate.

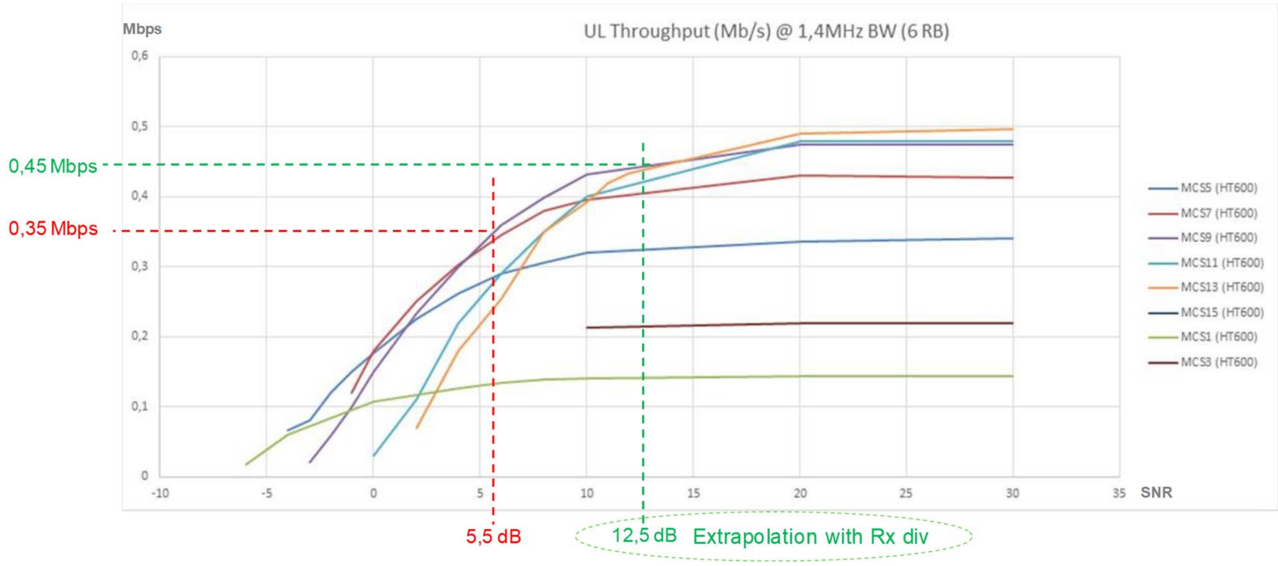



**Figure 9: Measurement results for 1,4 MHz channel BW**

The measurements are made on a per MCS (Modulation Coding Scheme) basis. On real conditions, an adaptive feature (AMC: Adaptive Modulation Coding) will be used to get access to the envelope of all results.

The minimum data throughput is obtained with 17 dBi antenna and without Rx diversity. This corresponds to 5,5 dB SNR and offers 0,35 Mbps data throughput.

Using 21 dBi antenna and with Rx diversity 3 dB minimum gain, SNR reaches 12,5 dB which corresponds to 0,45 Mbps.

Similar curves for 3 MHz with 360 km/h and 500 km/h are given in Annex C.

Results are summarized in Table 9.

**Table 9: Guaranteed data throughput at HO point**

| Data throughput (Mbps) | | 17 dBi ant gain | | 21 dBi ant gain | |
|---|---|---|---|---|---|
| | | Rx diversity | | Rx diversity | |
| LTE Ch BW | Speed (km/h) | Without | With | Without | With |
| 3 | 360 | 0,61 | 0,81 | 0,9 | 1,05 |
| 3 | 500 | 0,42 | 0,55 | 0,6 | 0,68 |
| 1,4 | 360 | 0,35 | 0,43 | 0,4 | 0,45 |

It is believed that actual results in the field would be better and this is explained in clause 5.3.4.

## 5.3.4 Notes and remarks

The actual performance in the field could be better than the results of these experiments:

- Hilly Terrain is simulated with 6 taps. However, during experiments it has been noticed that a richer environment has a positive impact on data throughput. ETSI TS 145 005 [i.1] offers the possibility of Hilly Terrain with 12 taps. Using this set-up gave higher data throughput.
- Rx diversity. Actual diversity in the field offers 3 dB gain at minimum gain. However, practical gain is higher since Rx diversity offers better processing possibilities for the signal.

- Extended CP could also be a key contributor to enhance data throughput. Latest echo for Hilly Terrain from ETSI TS 145 005 [i.1] Hilly Terrain profile is 20 μs later than main signal. Normal CP used in this experiment offers protection against ISI up to 4,6 μs, and extended CP offers protection up to 16 μs. It is expected that this could be beneficial for data throughput.
- Actual Doppler shift range could be lower in real life.
- MCS delivering best data throughput depends on propagation scenario. This is illustrated with the graph: "Maximum data rate per MCS vs. conditions (3 MHz)" in Annex C.

# 6 Results evaluation

## 6.1 Analysis

### 6.1.1 General

Table 10 summarizes the assumption differences between the evaluation sets §1 and §3 that seem to have the highest impact on throughput results.

**Table 10: Assumption differences between the evaluation sets**

| Result Set §1 | Results Set §3 | Remarks |
|---|---|---|
| Link simulation: channel and TX/Rx are simulated | Actual transmission devices, channel emulation | |
| System simulation including deployment impact, in particular including interference from neighbouring cells | One cell only. Interferences from neighbours not included in link budget | Interference is a strong limiting factor |
| Frequency-domain channel estimation: Wiener | Non Available | |
| Time-domain channel estimation: Time interpolation between pilots among and between sub-frames at receiver | Probably no interpolation | |
| Doppler model follows the spatial channel model (AoD/AoA) | Random Doppler shift ([i.1]) | |
| Commercial antenna diagram (KATHREIN) | Fixed antenna gain | The antenna diagram may have an impact on Doppler action |
| Gross throughput: Overhead of pilot signals and cyclic prefix included | Net payload throughput: All the protocol stack overhead is included | An estimation of protocol stack overhead is necessary to conclude |
| No HARQ | HARQ included (up to 4 retransmissions) | HARQ brings a gain in terms of PER, with a cost on delay and transmission resources |
| Extended CP | Normal CP | |

The two sets are not operating at the same level: Result Set §1 operates at *Software simulation reference point* while Result Set §3 operates at *Hardware simulation and laboratory test reference point*, see clause 4.2).

In the following, the term g*ross throughput* is used to refer to throughput corresponding to *Software simulation reference point* and *net throughput* the values obtained at *Hardware simulation and laboratory test reference point*.

### 6.1.2 Overheads analysis

#### 6.1.2.1 General

To better compare the Result Sets, it is necessary to understand and assess the difference lying below the *gross throughput* and the *net throughput* evaluations.

This clause assumes a static UE (i.e. train).

### 6.1.2.2 IP stack, PDCP and RLC overheads

IP stack overhead corresponds to the overhead of the IP/UDP used by the application, iperf in result set §3.

The PDCP may compress the IP header. Compression depends on the type of packet (IP/UDP, IP TCP, etc.), and compressor is a state machine, i.e. the compression ratio depends of the time and of the transport conditions. Considering one UE and a constant session, which is the scenario in the simulation/evaluation picture, PDCP could be expected to remove 20 bytes of IP header, and 8 bytes of the UDP header and replace them by 2 bytes.

MAC will add something like 4 bytes of overhead.

Then, even without header compression, considering maximum packet length of 1 500 octets, the overhead corresponds to something like 2 %, which is negligible (2,5 % with 1 024 octets packet length).

### 6.1.2.3 Physical layer overheads

Result Set §1 takes into account cyclic prefix and pilots overhead. But the PHY layer introduces additional overheads, related to control signalling such as PDCCH, and PBCH channels.

This overhead is different on UL and DL and depends on channel bandwidth, being more important with a small number of PRBs. This overhead is typically between 15 % and 30 %.

### 6.1.2.4 Link-level comparison

In order to get an upper absolute limit value, the computation of the maximum theoretical throughput is provided below, assuming no HARQ, but with pilots overhead and normal CP. The formula is provided for MCS20 (Modulation and Coding scheme) at 1.4 MHz, which corresponds to the highest MCS used in Result Set §3:

12 sub-Carriers x 6 RBs x 12 Symbols x 4 bits (16 QAM) x 0,74 FEC Rate / $10^{\wedge-3}$ (sub-frame duration) = 2,56 Mbps

To be able to compare more easily the different results, a set of (throughput vs. SNR) curves at link level step coming from simulation chain of Result Set §1 is shown in Figure 11, to be compared with curves coming from Result set §3 (Figure 10).

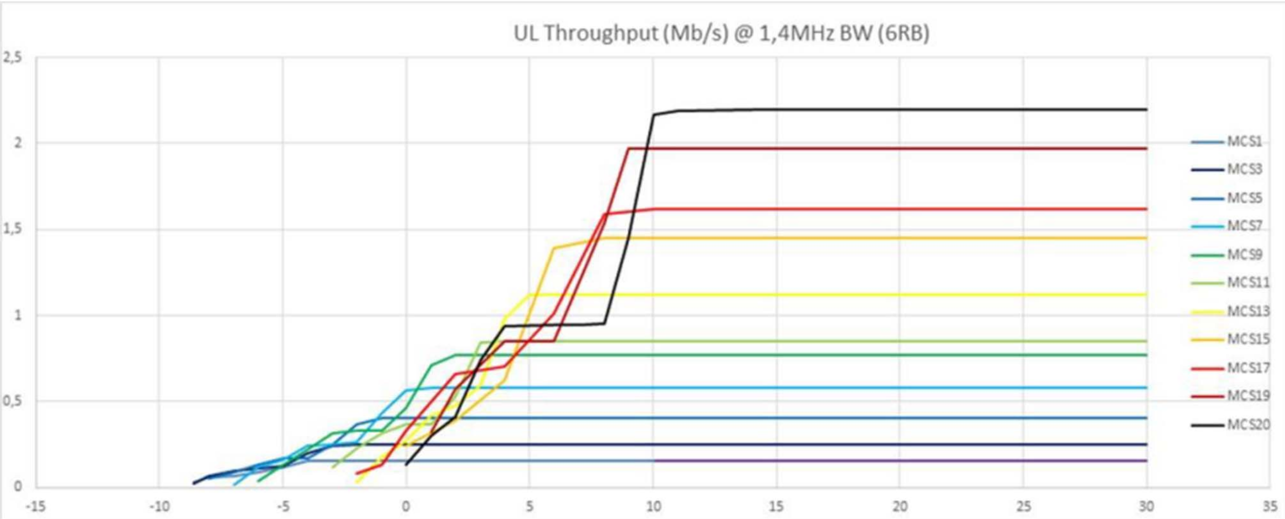



**Figure 10: Net UL throughput for a static UE in case of Result Set §3**

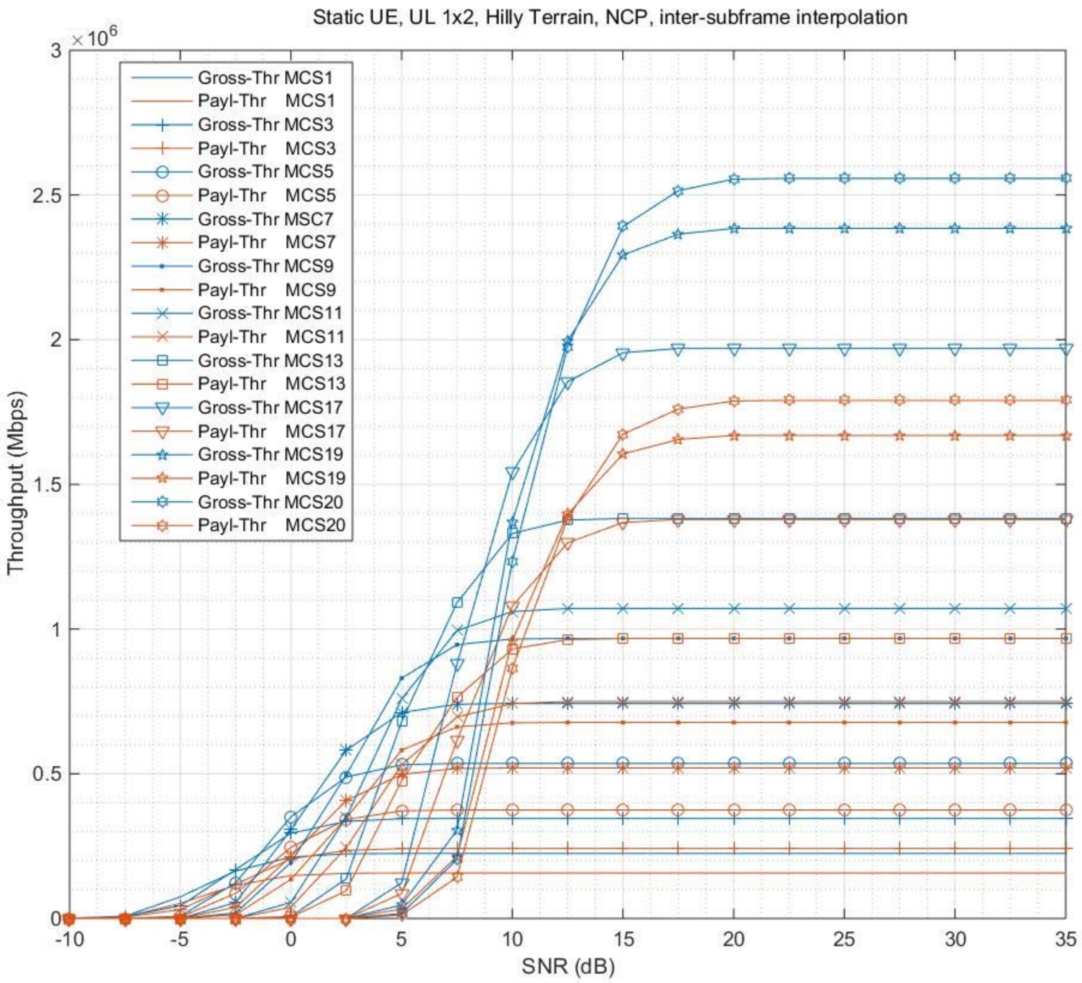



**Figure 11: UL throughput for a static UE in case of Result Set §1 (link simulation)**

For MCS 20, Result Set §3 gives a maximum throughput of 2,2 Mbit/s of net throughput. Result Set §1 gives 2,55 Mbit/s of gross throughput.

The difference between the 2 values is about 14 %, although the overhead for UL considering a 1.4 MHz bandwidth is likely to be more around 30 %. Moreover, the two sets of curves are shifted in SNR of about 10 dB: For this MCS 20, the maximum throughput is reached for a SNR of 10 dB in Result Set §3, and for a SNR around 20 dB for Result Set §1.

Hence, overhead cannot explain alone this difference.. There may be other factors impacting the results:

i) Result Set §1 assumes 2 antennas in reception, although only 1 is considered for Result Set §1. This could explain a +3 dB difference in favour of Set §1.

ii) A second factor is the HARQ which may provide between 7 to 10 dB gain [i.6] to Result Set §3.

Hence, gross throughput in UL has to be corrected by around 30 %, due to different overheads, but a gain of 7 to 10 could be expected with HARQ.

## 6.1.3 Train speed impact

This clause analyses the difference in Results Set §1 and Result Set §2 considering high train velocity. Figure 12 shows UL throughput for a UE at 350 km/h as provided by Result Set §3, while the UL throughput for a UE at 350 km/h at link simulation set up is provided in Figure 13.

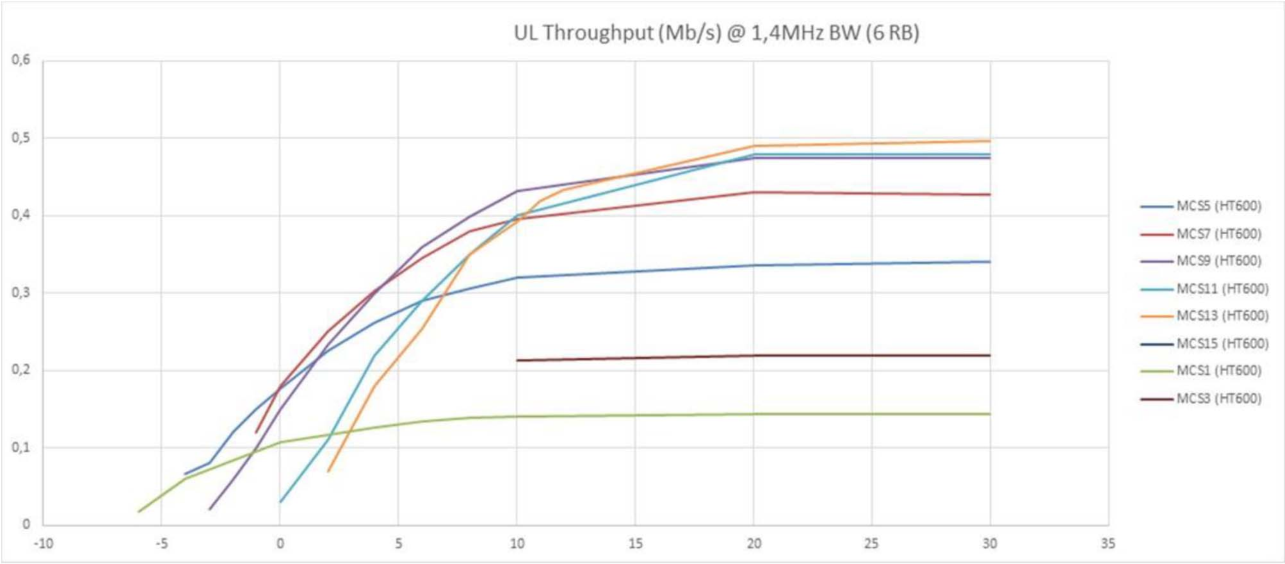



**Figure 12: Net UL throughput for a UE at 350 km/h for Result Set §3**

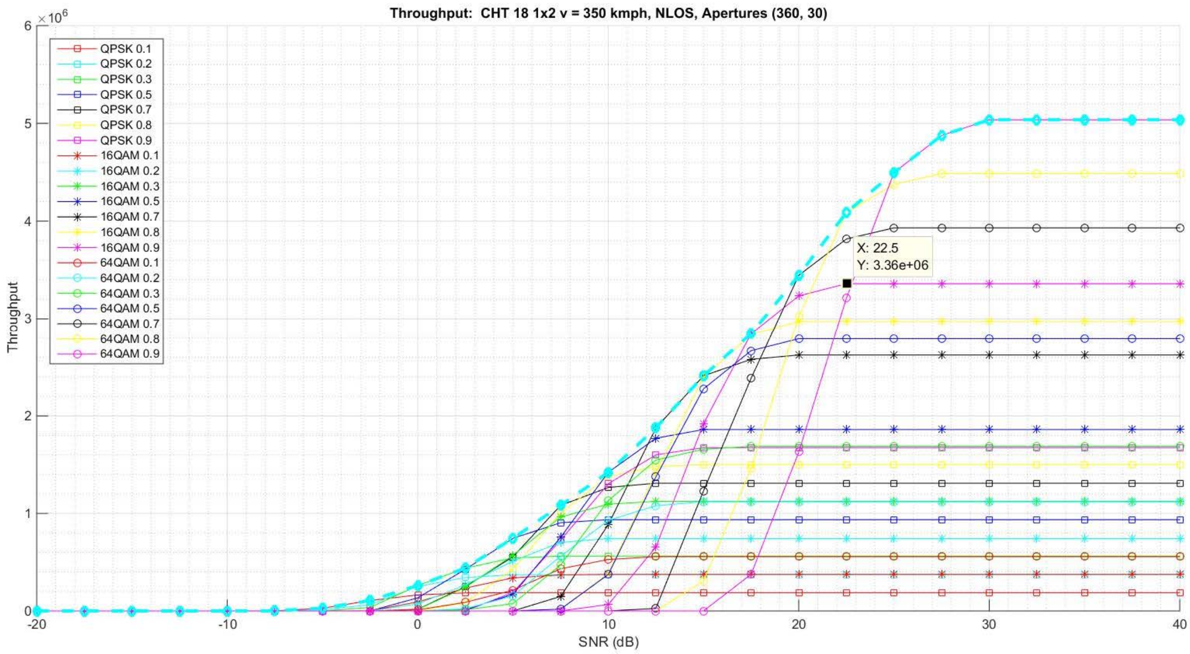



**Figure 13: UL throughput for a UE at 350 km/h for Result Set §1 (link simulation only)**

MCS 13 in Result Set §3, corresponding to 16QAM code rate 0,4, provides a max net throughput of 0,5 Mbit/s. A similar MCS in Result Set §1 indicates a gross throughput around 1,8 Mbit/s.

The difference may come from the following factors:

- Diversity gain due to the 2 Rx antenna assumed in Result Sets §1, while only 1 is present in Result Set §3
- Antenna diagram that filters the Doppler on paths arriving at high angles in Result Set §1
- Channel estimation time interpolation in Result Set §1

The impact of different factors has been evaluated with a link-level simulation for one MCS corresponding to MCS 20 (16 QAM code rate 0.7) of Result Set §3, as depicted in Figure 14. Blue curves provide the gross throughput, while a 30 % overhead is assumed in the red curves. Curves labelled "*AoA/D 2pi*" (Angle of Arrival/Departure) corresponds to a Doppler which is spread among 360 degrees, and curves labelled "*CDL*" corresponds to Doppler effect following a Cluster Delay Line model.

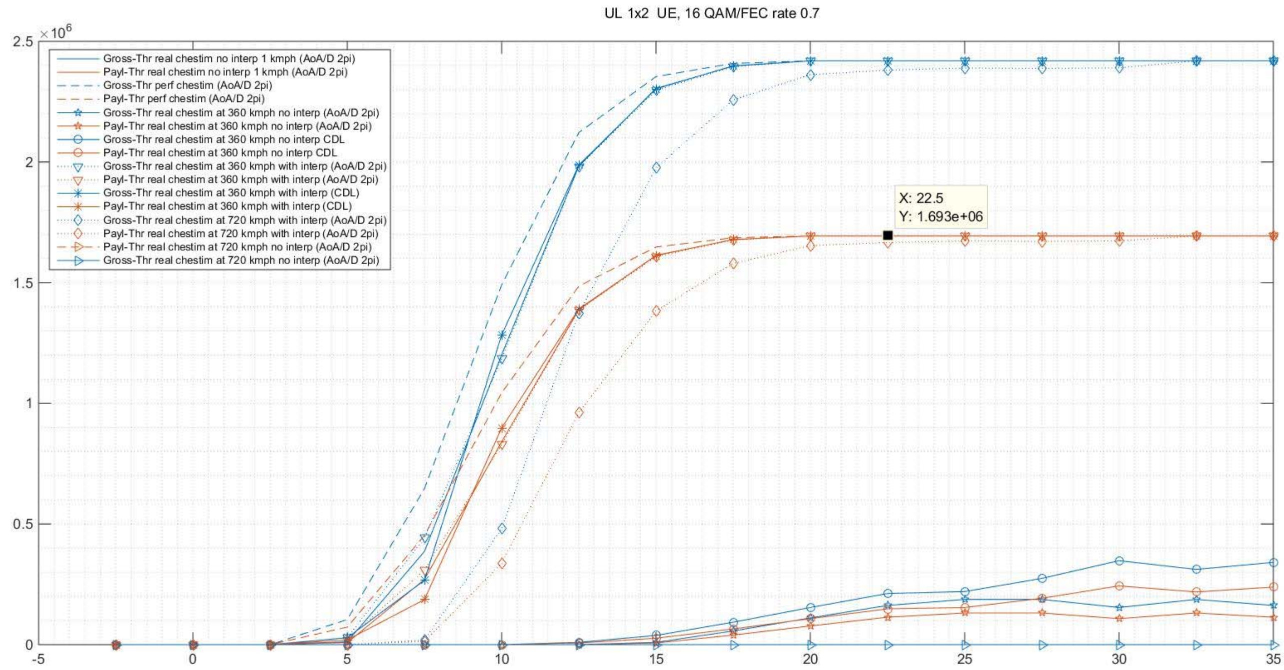



**Figure 14: Impact of Doppler model and channel estimation time interpolation on throughput**

The following can be observed:

- Channel estimation time interpolation has the main impact to fight against the Doppler.
- The effect of antenna filtering is noticeable, but of second order compared to channel estimation interpolation. With channel interpolation, the impact is clear in the intermediate SNR values (between 5 and 15 dB). With no interpolation and antenna diagram filtering, the maximum gross throughput is around 0,4 Mbit/s, to be compared to 0,2 Mbit/s with a random Doppler shift assumed.

The two last results are in the same order than Result Set §3, which shows 0.45 Mbit/s net max throughput, with a MCS 16 QAM code rate 0,4 (MCS 13) (which is more robust than MCS 20), and HARQ function on.

### 6.1.4 Neighbouring cells interference impact

Result Set §1 takes into account interference from neighbouring cells, and results shows that it is an important factor of the system performance that depends on neighbouring cell loads. Interference coordination has to be performed, for example with fractional frequency reuse techniques that could be implemented in a LTE system.

## 6.2 Identified system limitations

No limitations have been identified at this time. This clause will be completed when the study with 3 MHz and 5 MHz of bandwidth will be finalized.

# 7 Conclusion

It is to be noted that further analyses work needs to be performed, addressing, among other things, the effects of interference mitigation techniques and the effects of radio channels with different characteristics.

The assumptions considered in this study have been chosen to be stringent in order to test the system at its limits. In particular, a radio channel with a higher Rice factor (LOS component), which would lead to increased performance, could be encountered in the field.

Final conclusions on the use of LTE carriers for FRMCS may be drawn only after completion of these additional analyses. Nevertheless, this current version of the report allows drawing a set of initial conclusions.

Result set 3 includes a full LTE stack and provides net throughput values, but interferences from neighbours are not taken into account.

Result set 1 shows that interference can be a limiting factor if cells are operated in a frequency reuse 1 scheme and are fully loaded. However, LTE system has some flexibility in radio resource assignment and several interference mitigation techniques could be implemented, for example fractional frequency reuse. Therefore, and considering that 50 % load instead of 100 % load in all neighbouring cells is a more realistic assumption, it could be expected to have a minimum throughput at cell edge corresponding to results provided for frequency reuse 2 or 3 schemes.

Considering the two sets of results, a throughput in UL and DL in the range [0,3 - 0,4] Mbit/s could be expected as minimum guaranteed bit rate at handover point in a railway deployment, with a 1,4 MHz spectrum bandwidth in the 900 MHz band. This throughput is to be shared by trains served by the cell. Thanks to resource re-use techniques, this throughput could be made available at the same time on both sides of each site which could result in an increase of the total capacity available.

Results with a larger spectrum bandwidth, i.e. for operation in 3 or 5 MHz, and with a higher transmission power in UL (26 or 31 dBm), are also expected to significantly improve overall performances, at cell centre and at cell edge.

# Annex A: Theoretical peak throughput for LTE

Table A.1 provides the peak data rates at physical layer that are theoretically achievable by a LTE radio operating on a 1,4 MHz bandwidth, considering no packet loss (PER = 0), 64 QAM modulation, normal cyclic prefix and the following transmission schemes:

- The 2x2 MIMO transmission scheme is the Alamouti Space Frequency Block Code (SFBC) applied on two adjacent sub-carriers.
- The 4x2 MIMO transmission scheme is a combination of Alamouti SFBC and Frequency Switched Transmit Diversity (FSTD) on four adjacent sub-carriers.

Those transmission schemes have been selected among all schemes proposed by LTE standard for their high transmit diversity properties, which make them more robust to the high train velocity.

**Table A.1: Some maximum theoretical throughputs for LTE physical layer operating in a 1,4 MHz bandwidth**

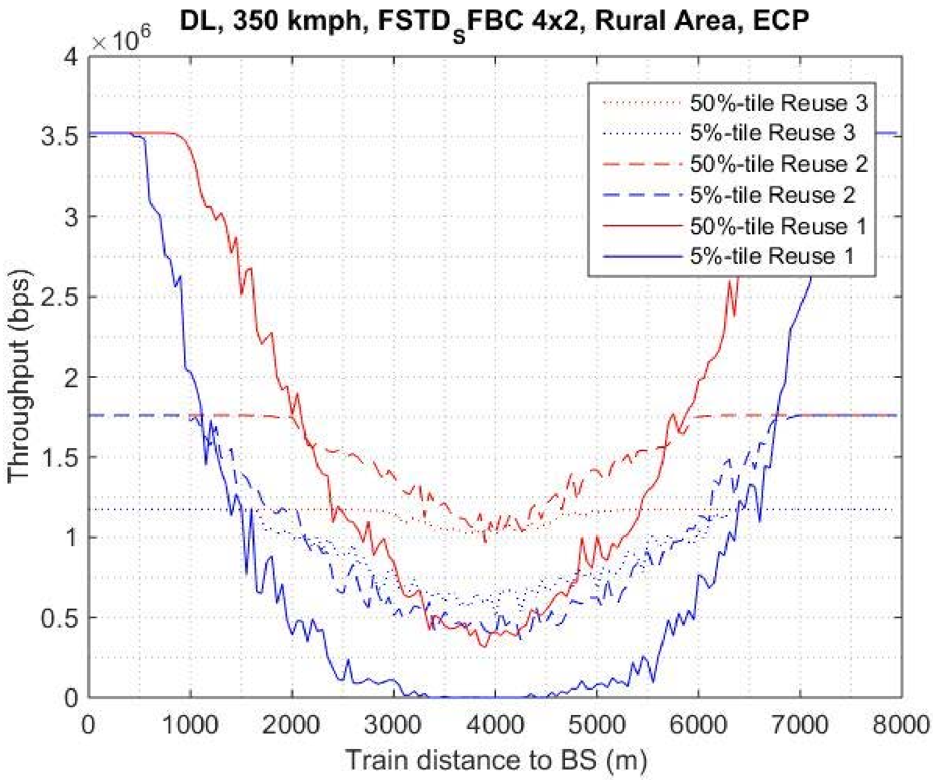
| Max. theoretical throughput (Mbps) | DL | | UL |
|---|---|---|---|
| | 2x2 (SFBC) | 4x2 (FSTD) | SIMO |
| Without control signalling overhead | 4,92 | 4,67 | 4,67 |
| With control signalling overhead<br>(2 OFDM symbols for PDCCH in DL, 2 PRBs for PUCCH in UL) | 4,75 | 4,61 | 3,46 |

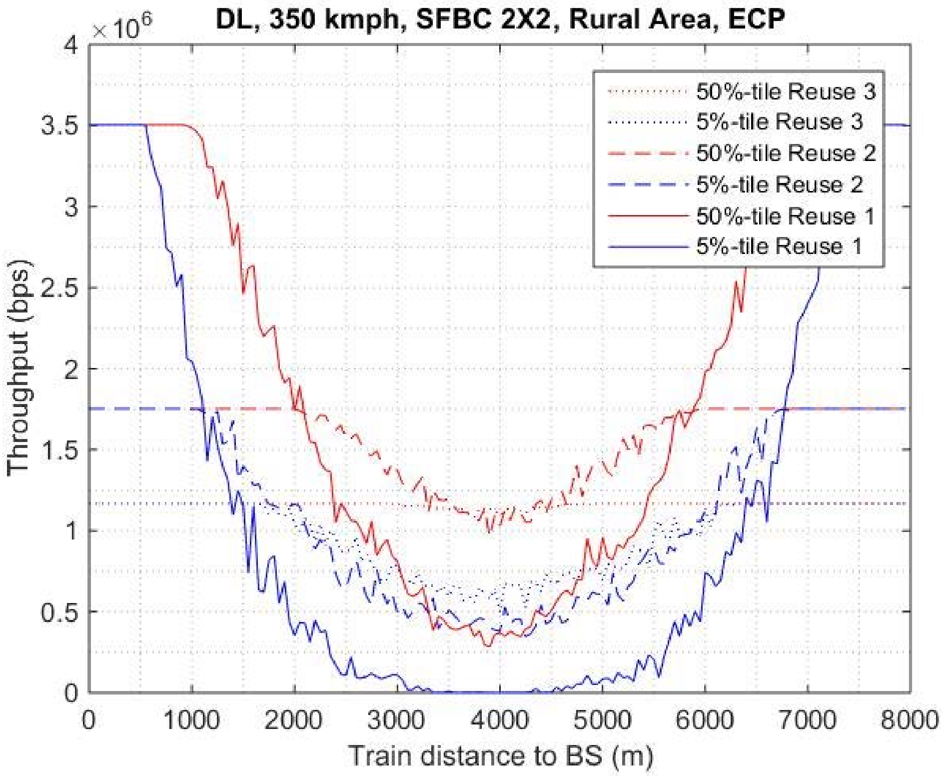
In DL, 4x2 transmission scheme has a peak throughput lower than 2x2 due to the increased pilot overhead (9,52 % for 2x2 against 14,29 % in 4x2), but is expected to be more resistant under bad radio conditions.

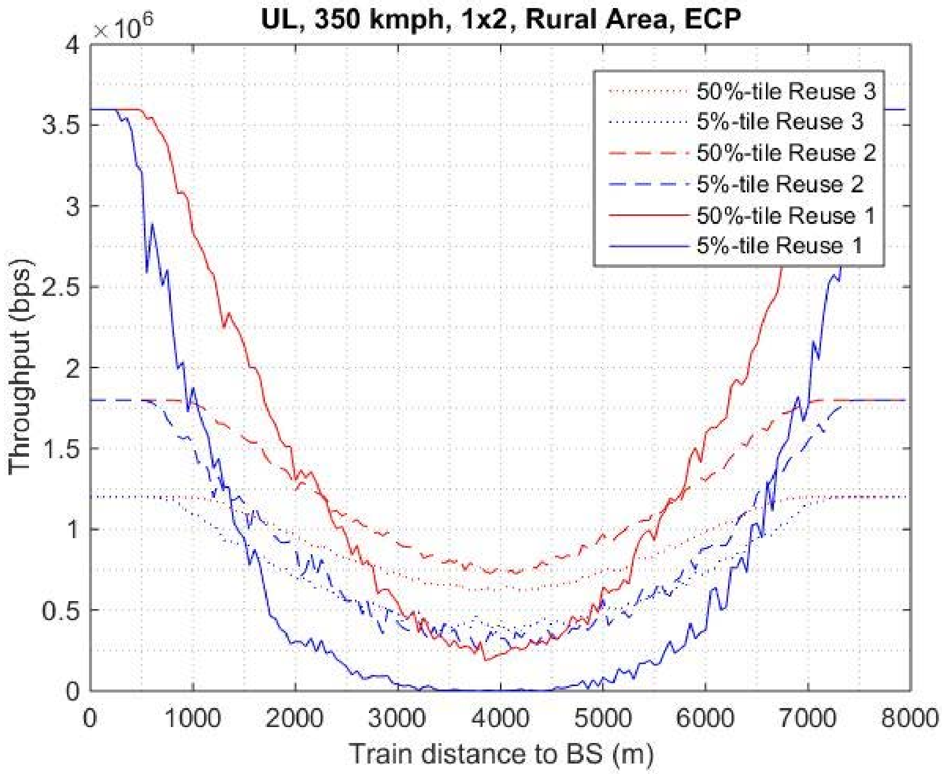
# Annex B: Throughput curves for simulation results set 1

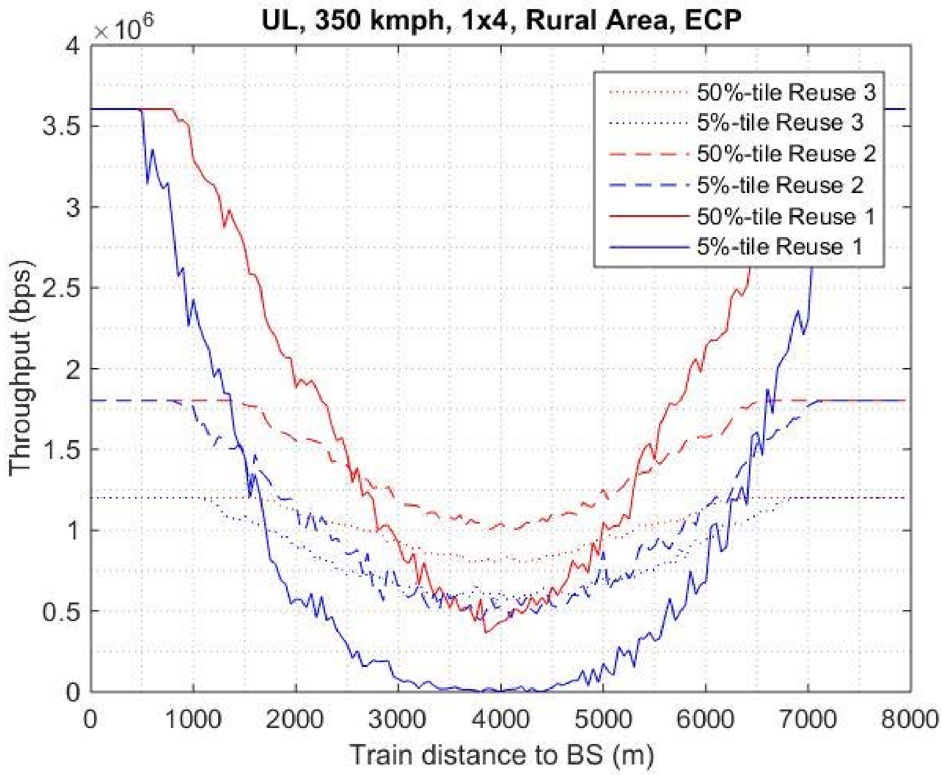
This annex provides the full set of (throughput vs distance to base station) curves for simulation results set 1.

**High speed scenario**

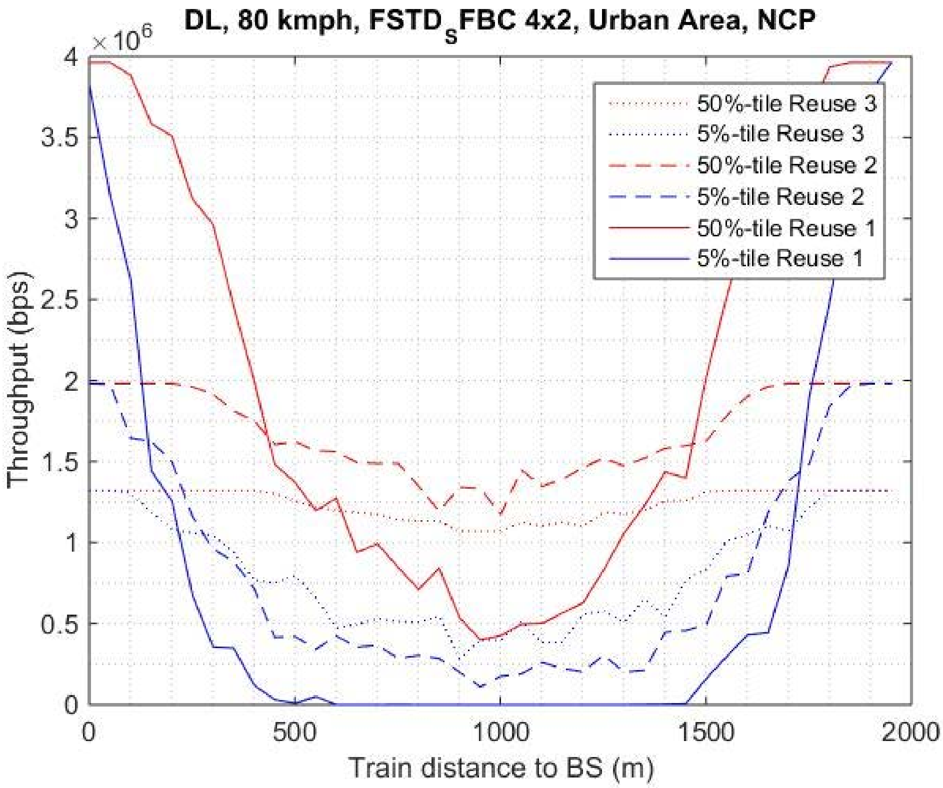


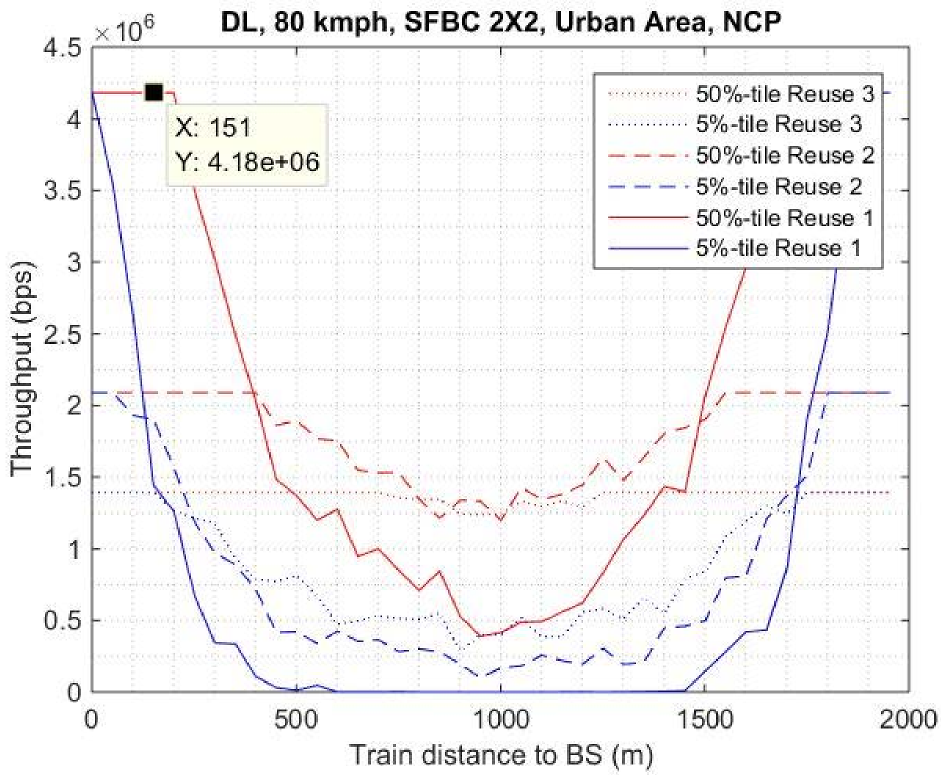

DL, 350 kmph, SFBC 2X2, Rural Area, ECP
× 10^6
4
3.5
3
2.5
2
1.5
1
0.5
0
Throughput (bps)
0
1000
2000
3000
4000
5000
6000
7000
8000
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1

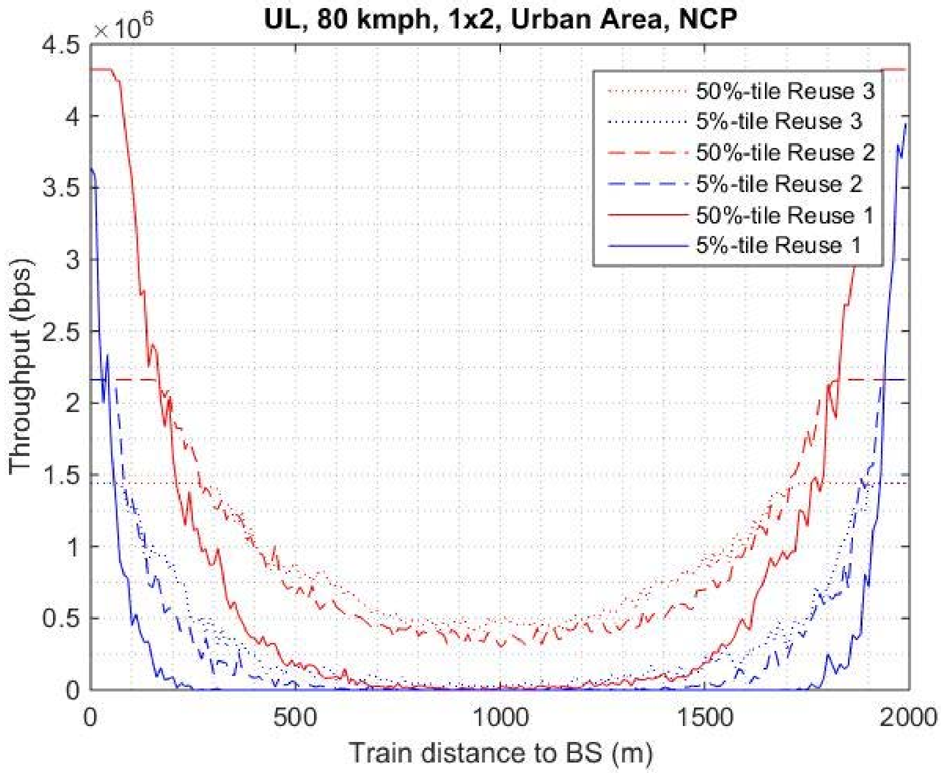

UL, 350 kmph, 1x2, Rural Area, ECP
×10^6
Throughput (bps)
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1
0
0.5
1
1.5
2
2.5
3
3.5
4
0
1000
2000
3000
4000
5000
6000
7000
8000

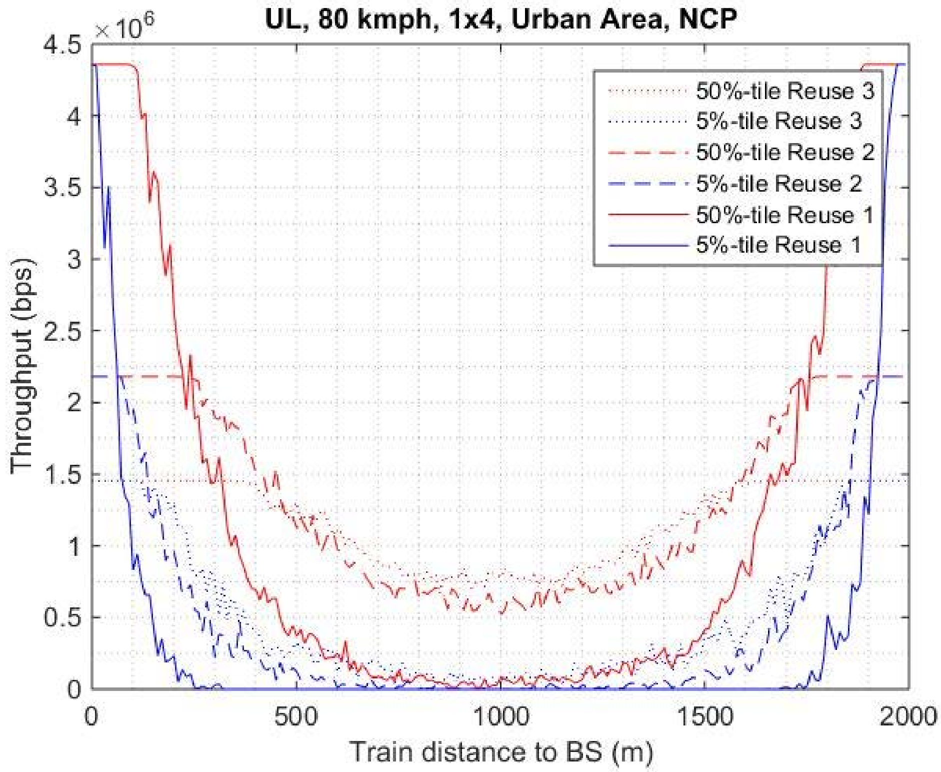

UL, 350 kmph, 1x4, Rural Area, ECP
×10^6
Throughput (bps)
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1
0
0.5
1
1.5
2
2.5
3
3.5
4
0
1000
2000
3000
4000
5000
6000
7000
8000

**Urban scenario**

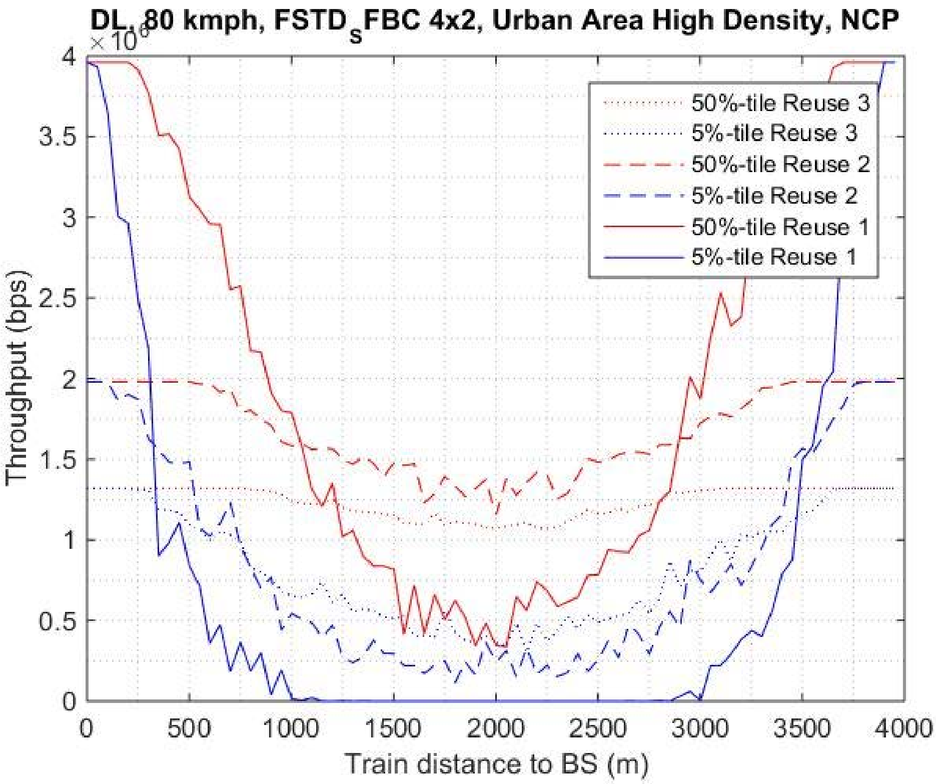


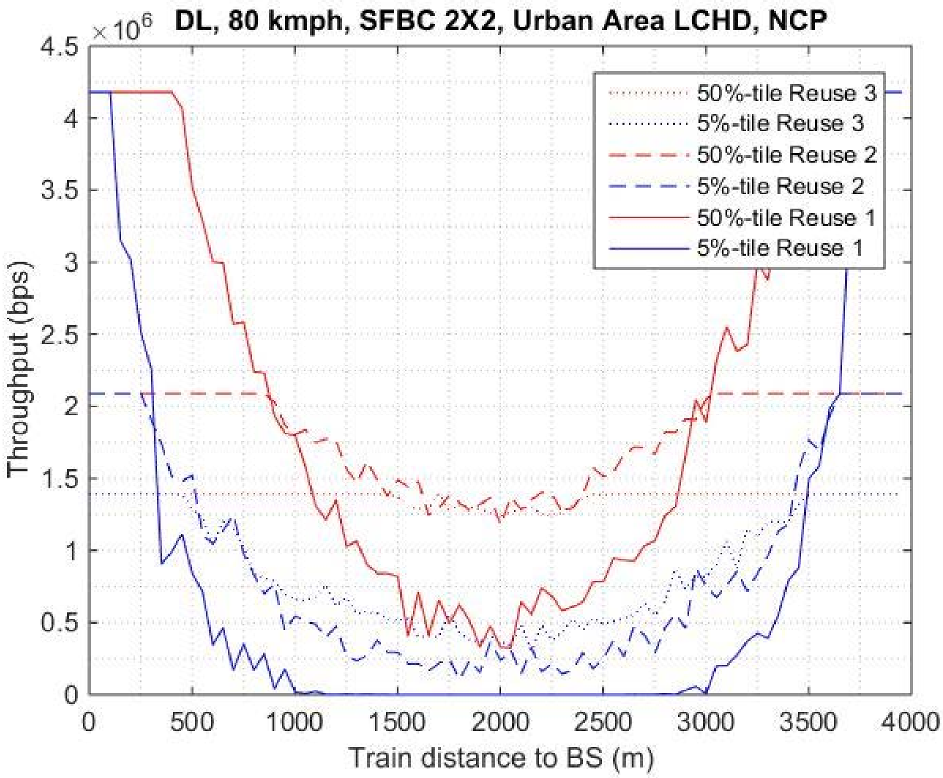



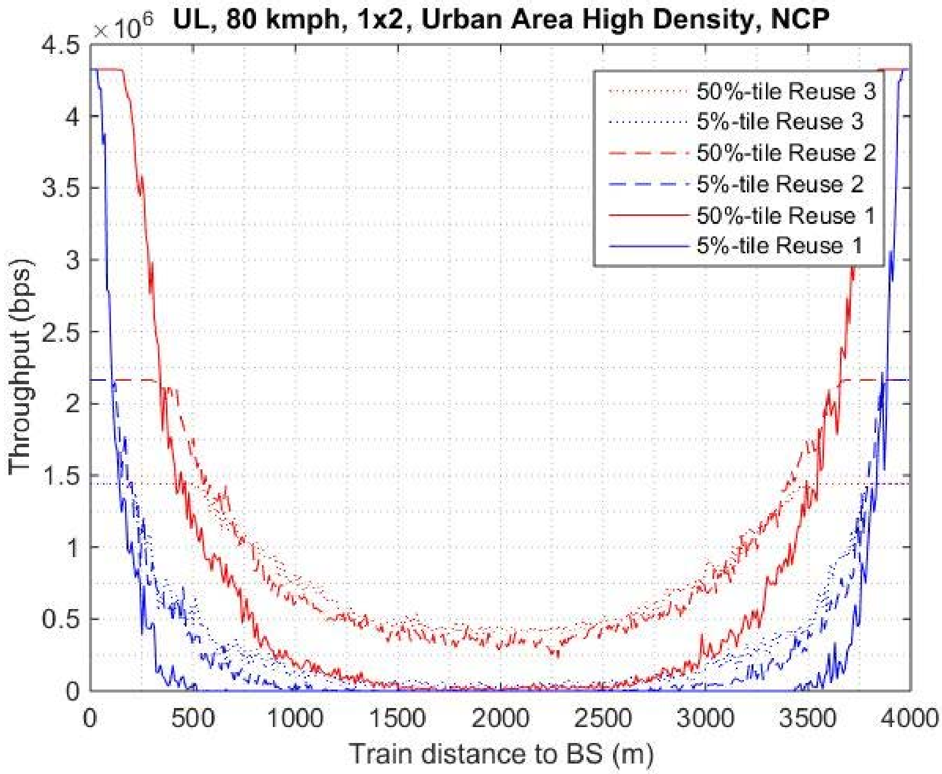

UL, 80 kmph, 1x2, Urban Area, NCP
×10^6
Throughput (bps)
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
500
1000
1500
2000

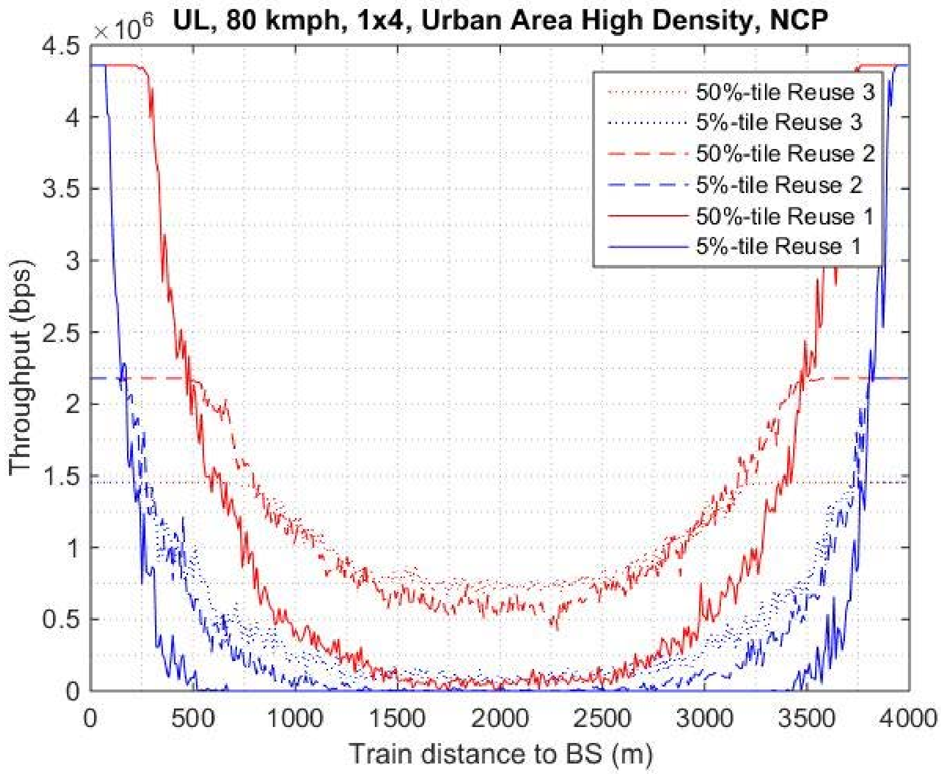

UL, 80 kmph, 1x4, Urban Area, NCP
×10^6
Throughput (bps)
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
500
1000
1500
2000

**High density scenario**

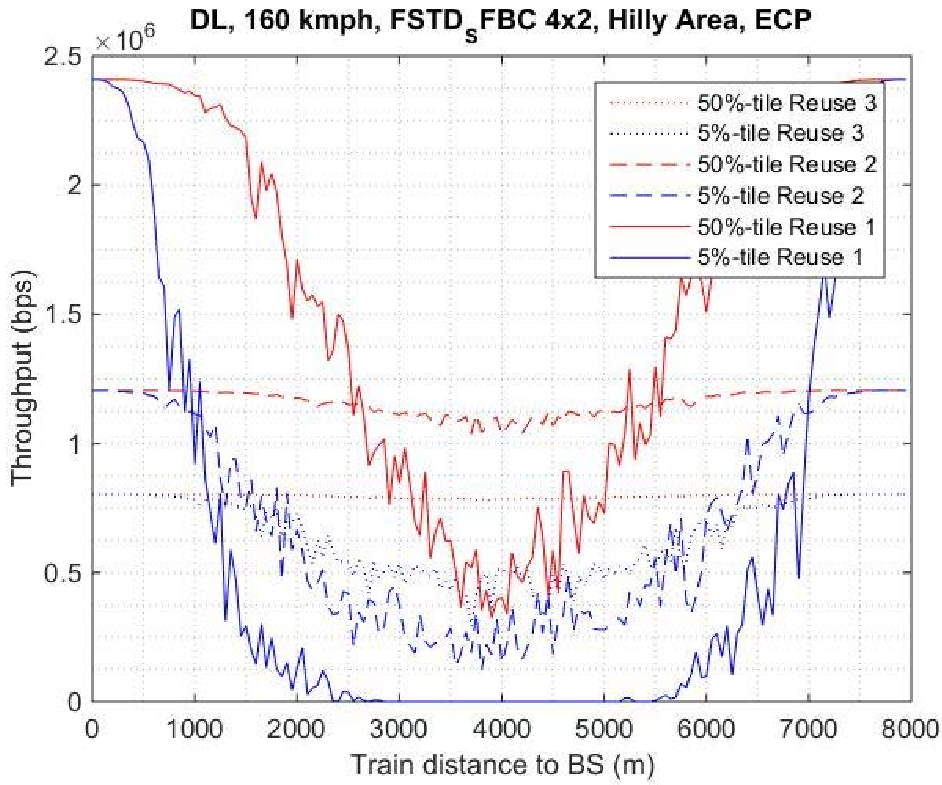


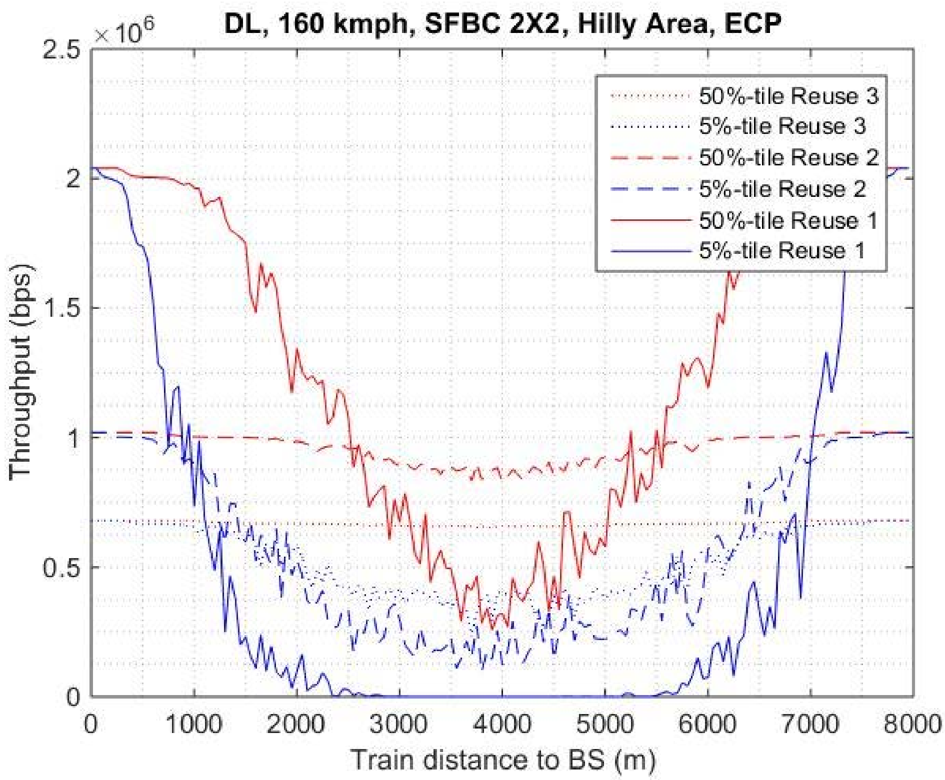



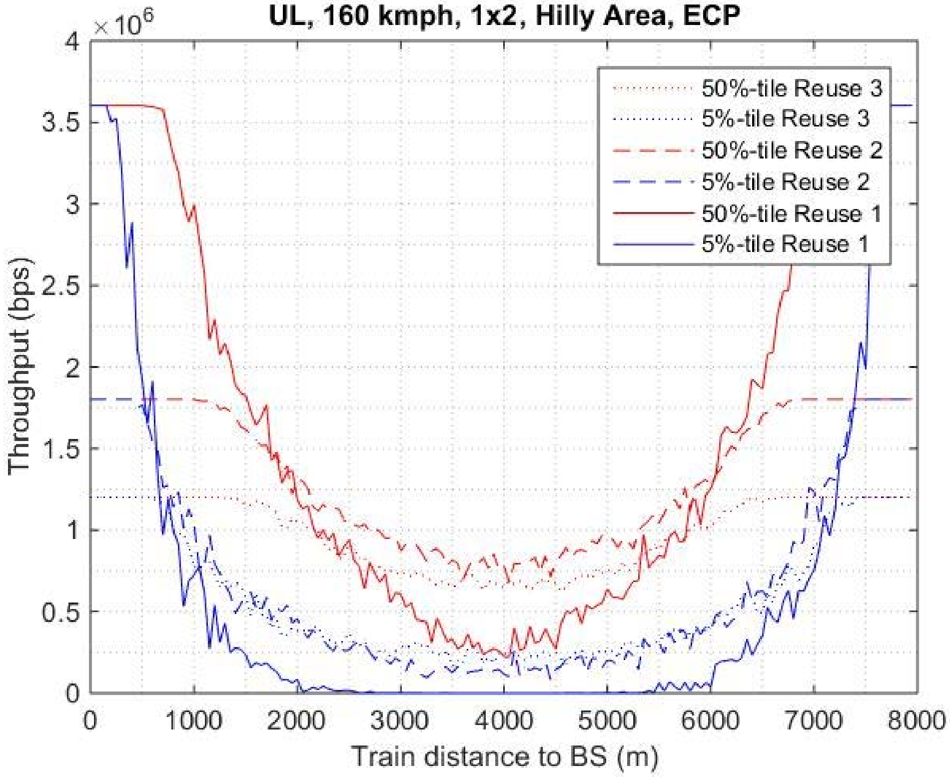

UL, 80 kmph, 1x2, Urban Area High Density, NCP
×10^6
Throughput (bps)
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
500
1000
1500
2000
2500
3000
3500
4000


UL, 80 kmph, 1x4, Urban Area High Density, NCP
×10^6
Throughput (bps)
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
500
1000
1500
2000
2500
3000
3500
4000

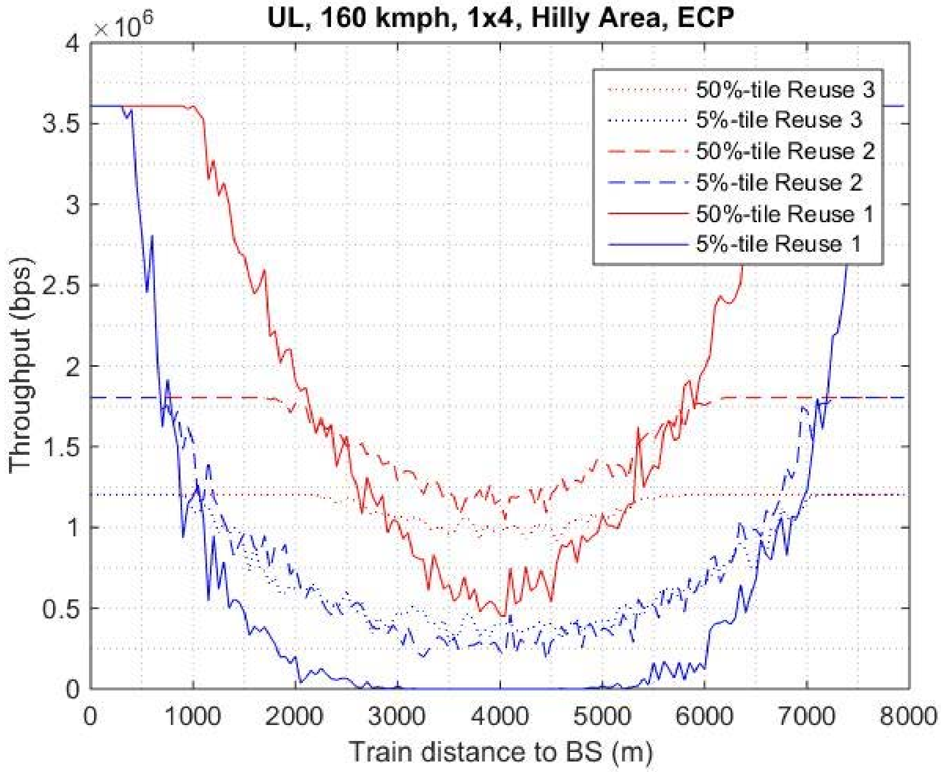
**Hilly scenario**



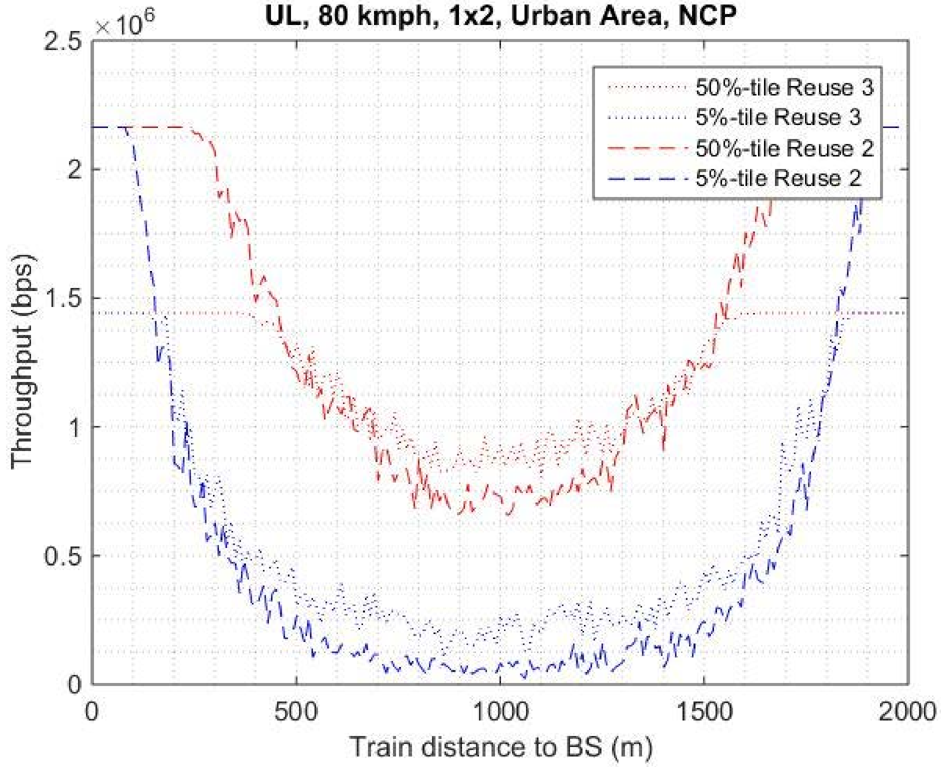


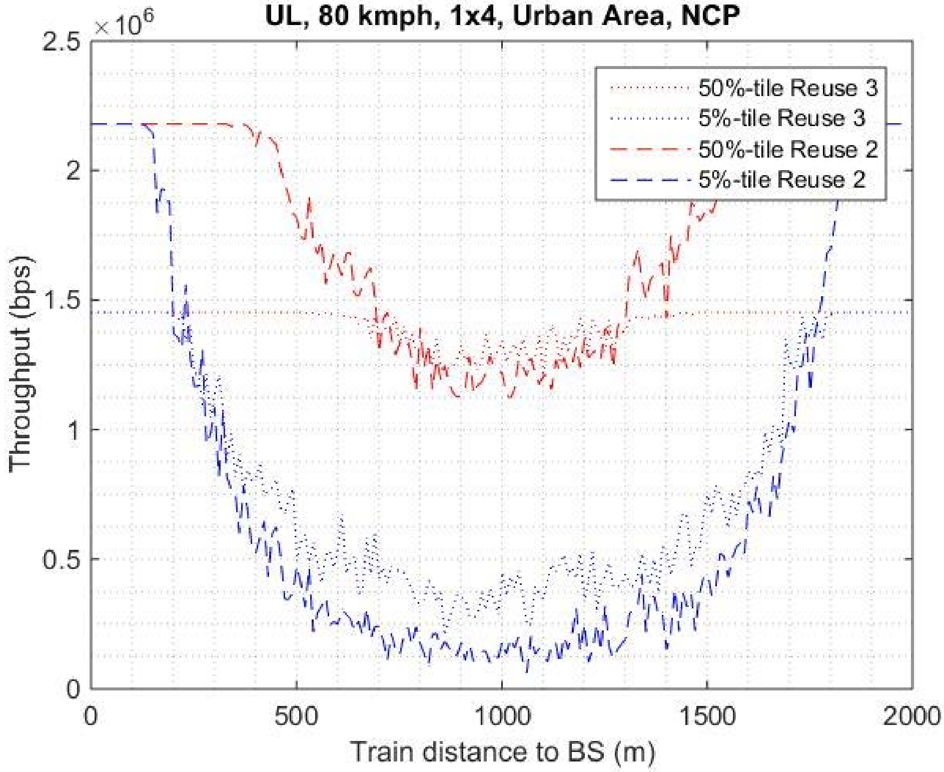
UL, 160 kmph, 1x2, Hilly Area, ECP
×10^6
4
3.5
3
2.5
2
1.5
1
0.5
0
Throughput (bps)
0
1000
2000
3000
4000
5000
6000
7000
8000
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1

UL, 160 kmph, 1x4, Hilly Area, ECP
×10^6
4
3.5
3
2.5
2
1.5
1
0.5
0
Throughput (bps)
0
1000
2000
3000
4000
5000
6000
7000
8000
Train distance to BS (m)
50%-tile Reuse 3
5%-tile Reuse 3
50%-tile Reuse 2
5%-tile Reuse 2
50%-tile Reuse 1
5%-tile Reuse 1

**Urban scenario with antenna tilt of 5°**

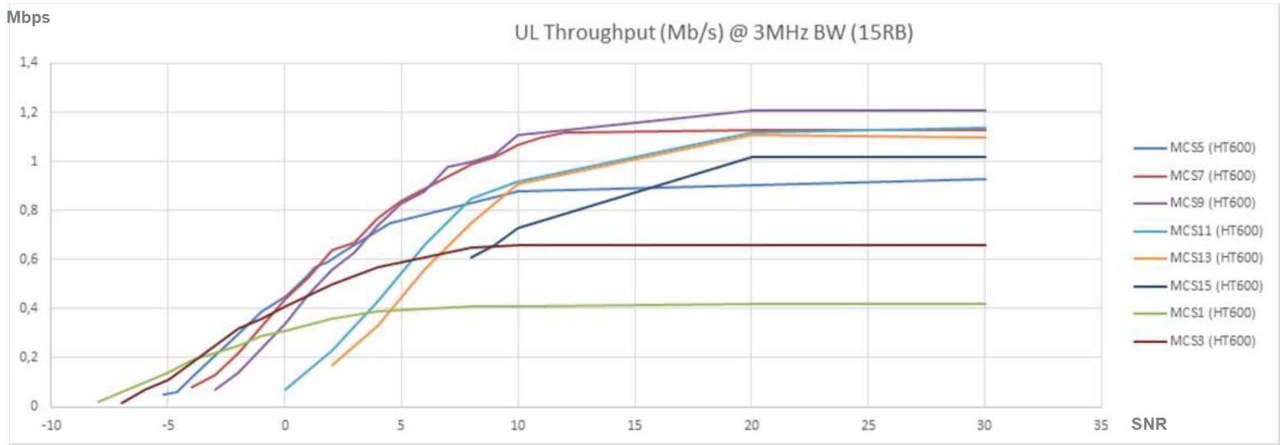


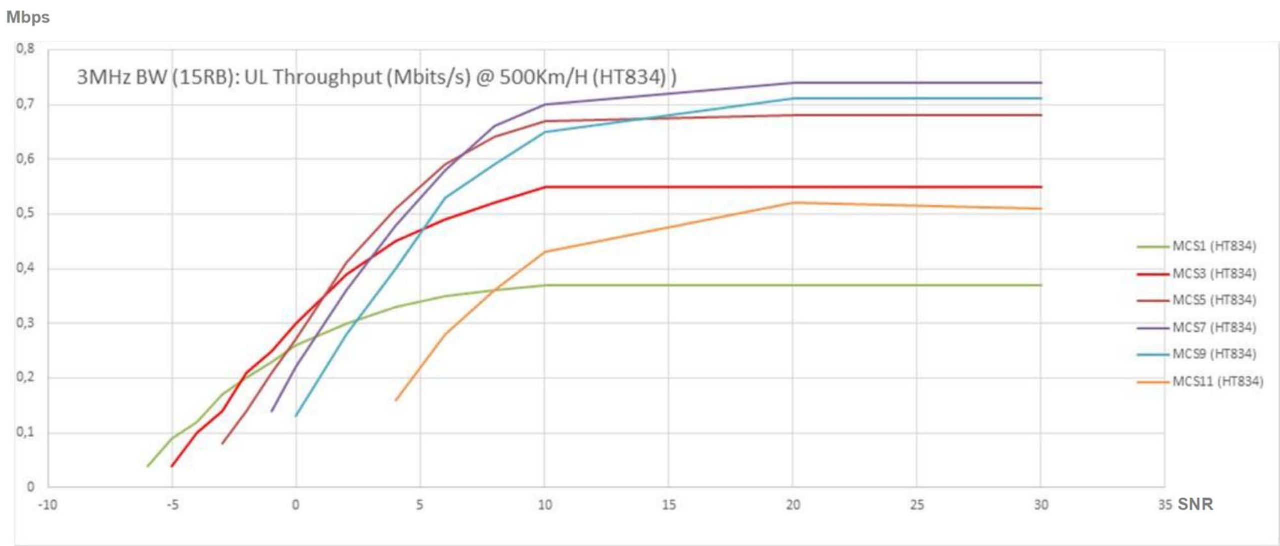
# Annex C: Data Throughput Measurements for results set 3

The following curves show UL throughput measurements obtained with the test bed described in clause 5.3.1, with UDP traffic using 1 024 bytes packet size.

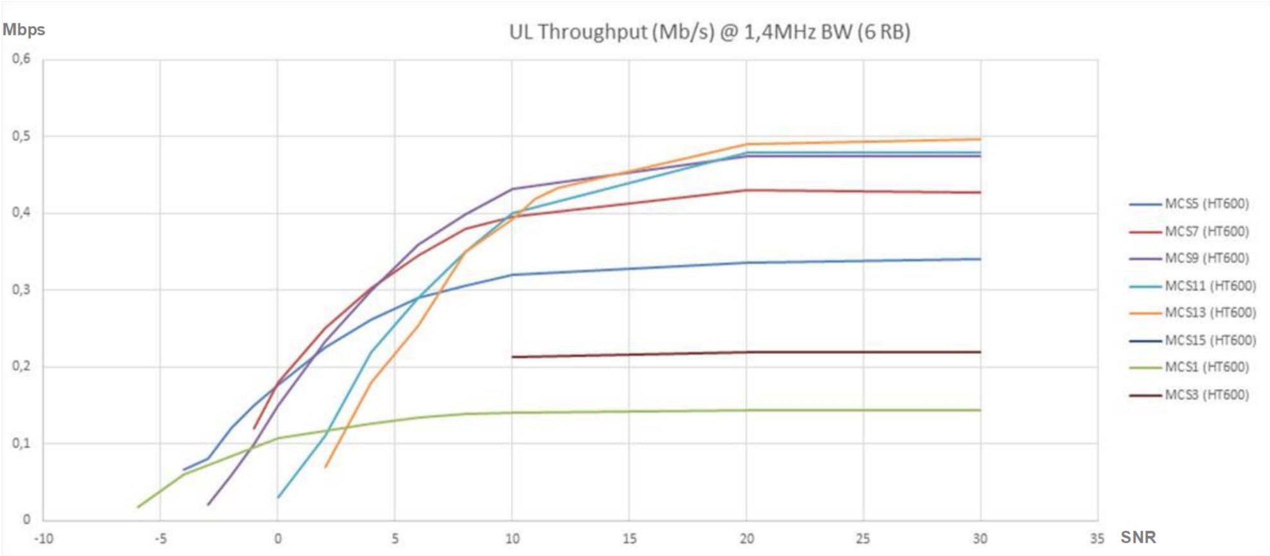
**LTE Channel Bandwidth = 3 MHz, Speed = 360 km/d Hilly Terrain with 6 taps**



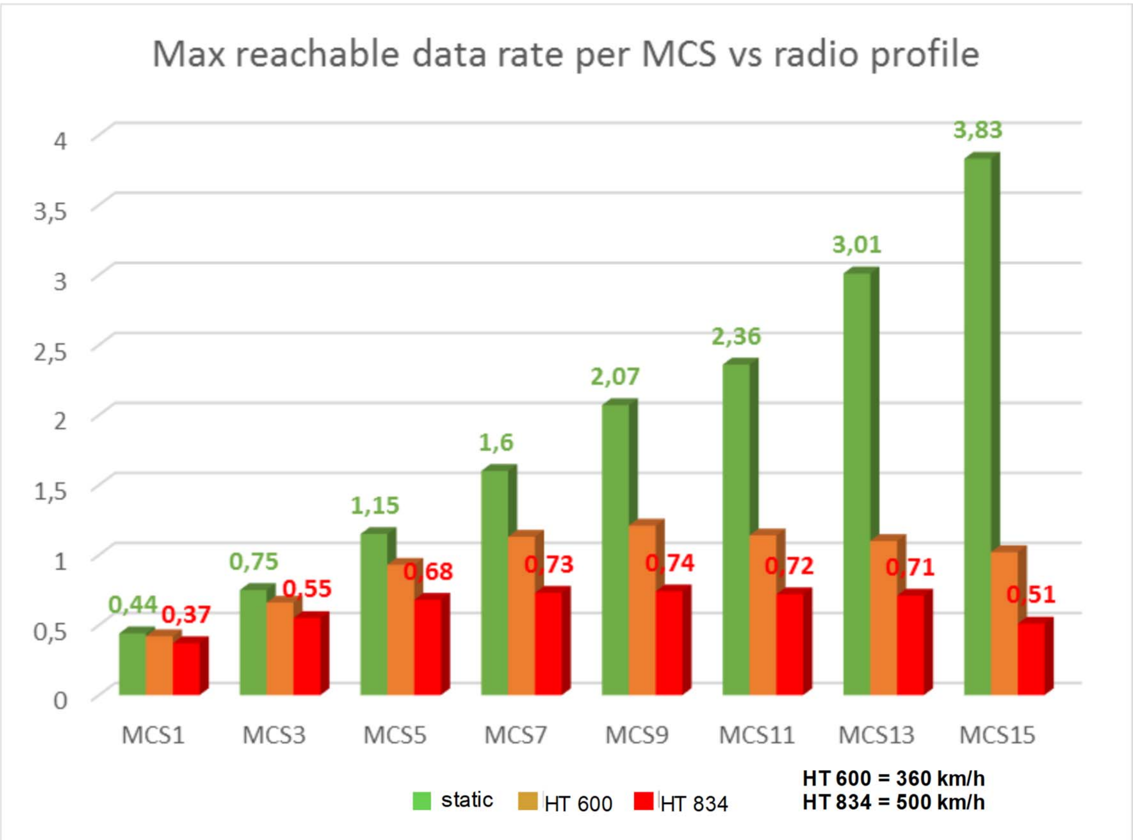

**LTE Channel Bandwidth = 3 MHz, Speed = 500 km/d Hilly Terrain with 6 taps**



**LTE Channel Bandwidth = 1,4 MHz, Speed = 360 km/h Hilly Terrain with 6 taps**




**Maximum data rate per MCS vs conditions (3 MHz)**



# Annex D: Antenna diagrams

### Antenna diagram 1

| Gain (dB) | Horizontal aperture (°) | Vertical aperture (°) |
|---|---|---|
| 20,5 | 30 | 8,5 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 0 | 0,00 | 0,00 |
| 1 | 0,02 | 0,18 |
| 2 | 0,06 | 0,71 |
| 3 | 0,13 | 1,61 |
| 4 | 0,23 | 2,92 |
| 5 | 0,35 | 4,67 |
| 6 | 0,50 | 6,97 |
| 7 | 0,67 | 9,99 |
| 8 | 0,87 | 14,07 |
| 9 | 1,10 | 20,09 |
| 10 | 1,35 | 28,71 |
| 11 | 1,63 | 24,72 |
| 12 | 1,94 | 20,96 |
| 13 | 2,28 | 19,66 |
| 14 | 2,64 | 19,85 |
| 15 | 3,04 | 21,32 |
| 16 | 3,47 | 24,29 |
| 17 | 3,94 | 28,98 |
| 18 | 4,45 | 29,38 |
| 19 | 5,01 | 24,68 |
| 20 | 5,62 | 21,56 |
| 21 | 6,29 | 19,86 |
| 22 | 7,02 | 19,20 |
| 23 | 7,81 | 19,42 |
| 24 | 8,67 | 20,50 |
| 25 | 9,60 | 22,54 |
| 26 | 10,61 | 25,71 |
| 27 | 11,70 | 29,83 |
| 28 | 12,89 | 31,65 |
| 29 | 14,22 | 29,83 |
| 30 | 15,71 | 28,58 |
| 31 | 17,43 | 28,86 |
| 32 | 19,50 | 30,69 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 33 | 22,00 | 33,28 |
| 34 | 25,02 | 32,18 |
| 35 | 28,06 | 28,39 |
| 36 | 28,67 | 25,48 |
| 37 | 26,40 | 23,63 |
| 38 | 23,87 | 22,58 |
| 39 | 21,82 | 22,16 |
| 40 | 20,23 | 22,27 |
| 41 | 18,98 | 22,86 |
| 42 | 17,95 | 23,91 |
| 43 | 17,09 | 25,47 |
| 44 | 16,36 | 27,64 |
| 45 | 15,75 | 30,53 |
| 46 | 15,21 | 33,85 |
| 47 | 14,76 | 35,28 |
| 48 | 14,39 | 33,44 |
| 49 | 14,08 | 31,29 |
| 50 | 13,84 | 29,93 |
| 51 | 13,65 | 29,34 |
| 52 | 13,52 | 29,44 |
| 53 | 13,42 | 30,19 |
| 54 | 13,35 | 31,63 |
| 55 | 13,32 | 33,93 |
| 56 | 13,31 | 37,62 |
| 57 | 13,32 | 44,70 |
| 58 | 13,36 | 54,87 |
| 59 | 13,41 | 41,09 |
| 60 | 13,49 | 36,15 |
| 61 | 13,59 | 33,23 |
| 62 | 13,71 | 31,24 |
| 63 | 13,84 | 29,81 |
| 64 | 13,98 | 28,77 |
| 65 | 14,14 | 28,04 |
| 66 | 14,32 | 27,54 |
| 67 | 14,51 | 27,23 |
| 68 | 14,71 | 27,07 |
| 69 | 14,93 | 27,04 |
| 70 | 15,17 | 27,11 |
| 71 | 15,41 | 27,28 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 72 | 15,66 | 27,56 |
| 73 | 15,93 | 27,95 |
| 74 | 16,19 | 28,43 |
| 75 | 16,46 | 28,99 |
| 76 | 16,74 | 29,57 |
| 77 | 17,02 | 30,11 |
| 78 | 17,31 | 30,55 |
| 79 | 17,60 | 30,85 |
| 80 | 17,90 | 31,04 |
| 81 | 18,21 | 31,16 |
| 82 | 18,52 | 31,27 |
| 83 | 18,83 | 31,42 |
| 84 | 19,14 | 31,64 |
| 85 | 19,44 | 31,94 |
| 86 | 19,75 | 32,30 |
| 87 | 20,06 | 32,71 |
| 88 | 20,37 | 33,16 |
| 89 | 20,68 | 33,64 |
| 90 | 20,99 | 34,14 |
| 91 | 21,31 | 34,66 |
| 92 | 21,64 | 35,14 |
| 93 | 21,96 | 35,55 |
| 94 | 22,29 | 35,88 |
| 95 | 22,63 | 36,16 |
| 96 | 22,96 | 36,50 |
| 97 | 23,29 | 37,03 |
| 98 | 23,62 | 37,90 |
| 99 | 23,94 | 39,27 |
| 100 | 24,25 | 41,27 |
| 101 | 24,55 | 43,83 |
| 102 | 24,84 | 45,94 |
| 103 | 25,12 | 45,82 |
| 104 | 25,39 | 44,50 |
| 105 | 25,66 | 43,70 |
| 106 | 25,93 | 43,81 |
| 107 | 26,18 | 44,61 |
| 108 | 26,44 | 45,20 |
| 109 | 26,69 | 44,40 |
| 110 | 26,93 | 42,65 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 111 | 27,18 | 41,08 |
| 112 | 27,41 | 40,07 |
| 113 | 27,62 | 39,61 |
| 114 | 27,82 | 39,55 |
| 115 | 27,99 | 39,67 |
| 116 | 28,13 | 39,71 |
| 117 | 28,23 | 39,45 |
| 118 | 28,33 | 38,82 |
| 119 | 28,41 | 37,91 |
| 120 | 28,50 | 36,93 |
| 121 | 28,59 | 36,07 |
| 122 | 28,72 | 35,47 |
| 123 | 28,86 | 35,19 |
| 124 | 29,00 | 35,25 |
| 125 | 29,12 | 35,60 |
| 126 | 29,23 | 36,12 |
| 127 | 29,29 | 36,64 |
| 128 | 29,33 | 37,00 |
| 129 | 29,36 | 37,14 |
| 130 | 29,41 | 37,11 |
| 131 | 29,50 | 37,01 |
| 132 | 29,63 | 36,90 |
| 133 | 29,82 | 36,80 |
| 134 | 30,06 | 36,80 |
| 135 | 30,33 | 36,97 |
| 136 | 30,60 | 37,39 |
| 137 | 30,87 | 38,05 |
| 138 | 31,14 | 38,79 |
| 139 | 31,40 | 39,16 |
| 140 | 31,67 | 38,74 |
| 141 | 31,99 | 37,64 |
| 142 | 32,39 | 36,40 |
| 143 | 32,85 | 35,40 |
| 144 | 33,39 | 34,79 |
| 145 | 33,98 | 34,64 |
| 146 | 34,59 | 34,96 |
| 147 | 35,16 | 35,78 |
| 148 | 35,68 | 37,03 |
| 149 | 36,13 | 38,53 |
| 150 | 36,50 | 39,91 |
| 151 | 36,79 | 40,82 |
| 152 | 37,02 | 41,44 |
| 153 | 37,21 | 42,30 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 154 | 37,29 | 43,65 |
| 155 | 37,25 | 44,69 |
| 156 | 37,08 | 43,97 |
| 157 | 36,79 | 42,25 |
| 158 | 36,40 | 40,97 |
| 159 | 35,97 | 40,42 |
| 160 | 35,51 | 40,23 |
| 161 | 35,07 | 39,65 |
| 162 | 34,65 | 38,45 |
| 163 | 34,28 | 37,21 |
| 164 | 33,96 | 36,56 |
| 165 | 33,69 | 36,78 |
| 166 | 33,47 | 38,09 |
| 167 | 33,31 | 40,75 |
| 168 | 33,19 | 45,28 |
| 169 | 33,10 | 51,94 |
| 170 | 33,03 | 54,18 |
| 171 | 32,98 | 53,77 |
| 172 | 32,95 | 52,67 |
| 173 | 32,94 | 45,92 |
| 174 | 32,98 | 40,70 |
| 175 | 33,07 | 37,39 |
| 176 | 33,23 | 35,42 |
| 177 | 33,44 | 34,46 |
| 178 | 33,70 | 34,36 |
| 179 | 34,01 | 35,06 |
| 180 | 34,37 | 36,55 |
| 181 | 34,69 | 38,89 |
| 182 | 34,99 | 42,00 |
| 183 | 35,26 | 44,68 |
| 184 | 35,51 | 44,51 |
| 185 | 35,77 | 42,92 |
| 186 | 36,07 | 41,89 |
| 187 | 36,42 | 41,66 |
| 188 | 36,83 | 42,03 |
| 189 | 37,29 | 42,62 |
| 190 | 37,82 | 42,97 |
| 191 | 38,38 | 42,72 |
| 192 | 38,94 | 41,75 |
| 193 | 39,49 | 40,32 |
| 194 | 40,03 | 38,82 |
| 195 | 40,49 | 37,64 |
| 196 | 40,89 | 37,01 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 197 | 41,21 | 37,02 |
| 198 | 41,46 | 37,68 |
| 199 | 41,63 | 38,78 |
| 200 | 41,75 | 39,62 |
| 201 | 41,82 | 39,26 |
| 202 | 41,81 | 37,84 |
| 203 | 41,69 | 36,27 |
| 204 | 41,45 | 35,01 |
| 205 | 41,10 | 34,18 |
| 206 | 40,62 | 33,83 |
| 207 | 40,08 | 34,01 |
| 208 | 39,56 | 34,78 |
| 209 | 39,12 | 36,18 |
| 210 | 38,74 | 37,94 |
| 211 | 38,42 | 38,99 |
| 212 | 38,21 | 38,26 |
| 213 | 38,02 | 36,75 |
| 214 | 37,82 | 35,65 |
| 215 | 37,57 | 35,28 |
| 216 | 37,30 | 35,72 |
| 217 | 37,01 | 37,03 |
| 218 | 36,70 | 39,37 |
| 219 | 36,43 | 43,20 |
| 220 | 36,24 | 49,56 |
| 221 | 36,13 | 52,60 |
| 222 | 36,07 | 46,94 |
| 223 | 36,09 | 43,92 |
| 224 | 36,14 | 42,66 |
| 225 | 36,20 | 42,58 |
| 226 | 36,19 | 43,58 |
| 227 | 36,16 | 45,92 |
| 228 | 36,10 | 50,69 |
| 229 | 36,00 | 63,80 |
| 230 | 35,89 | 52,12 |
| 231 | 35,80 | 45,70 |
| 232 | 35,75 | 42,16 |
| 233 | 35,70 | 39,85 |
| 234 | 35,64 | 38,25 |
| 235 | 35,56 | 37,16 |
| 236 | 35,45 | 36,49 |
| 237 | 35,27 | 36,21 |
| 238 | 35,04 | 36,32 |
| 239 | 34,80 | 36,88 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 240 | 34,55 | 37,93 |
| 241 | 34,30 | 39,62 |
| 242 | 34,05 | 42,15 |
| 243 | 33,82 | 45,75 |
| 244 | 33,57 | 48,75 |
| 245 | 33,28 | 46,31 |
| 246 | 32,93 | 42,68 |
| 247 | 32,55 | 40,03 |
| 248 | 32,12 | 38,15 |
| 249 | 31,64 | 36,75 |
| 250 | 31,16 | 35,64 |
| 251 | 30,68 | 34,73 |
| 252 | 30,23 | 33,95 |
| 253 | 29,79 | 33,29 |
| 254 | 29,39 | 32,72 |
| 255 | 29,00 | 32,24 |
| 256 | 28,61 | 31,85 |
| 257 | 28,21 | 31,55 |
| 258 | 27,80 | 31,32 |
| 259 | 27,37 | 31,13 |
| 260 | 26,93 | 30,95 |
| 261 | 26,47 | 30,74 |
| 262 | 26,02 | 30,46 |
| 263 | 25,58 | 30,12 |
| 264 | 25,14 | 29,73 |
| 265 | 24,72 | 29,32 |
| 266 | 24,31 | 28,92 |
| 267 | 23,91 | 28,55 |
| 268 | 23,50 | 28,21 |
| 269 | 23,10 | 27,88 |
| 270 | 22,69 | 27,53 |
| 271 | 22,27 | 27,12 |
| 272 | 21,85 | 26,65 |
| 273 | 21,44 | 26,10 |
| 274 | 21,03 | 25,50 |
| 275 | 20,64 | 24,88 |
| 276 | 20,25 | 24,28 |
| 277 | 19,86 | 23,70 |
| 278 | 19,49 | 23,17 |
| 279 | 19,11 | 22,67 |
| 280 | 18,73 | 22,18 |
| 281 | 18,36 | 21,69 |
| 282 | 17,99 | 21,17 |
| 283 | 17,63 | 20,64 |
| 284 | 17,27 | 20,11 |
| 285 | 16,94 | 19,60 |
| 286 | 16,61 | 19,13 |
| 287 | 16,30 | 18,75 |
| 288 | 16,00 | 18,45 |
| 289 | 15,71 | 18,26 |
| 290 | 15,43 | 18,18 |
| 291 | 15,16 | 18,20 |
| 292 | 14,90 | 18,31 |
| 293 | 14,65 | 18,53 |
| 294 | 14,42 | 18,84 |
| 295 | 14,21 | 19,26 |
| 296 | 14,01 | 19,81 |
| 297 | 13,84 | 20,52 |
| 298 | 13,68 | 21,46 |
| 299 | 13,54 | 22,69 |
| 300 | 13,41 | 24,33 |
| 301 | 13,31 | 26,55 |
| 302 | 13,23 | 29,66 |
| 303 | 13,18 | 34,20 |
| 304 | 13,16 | 39,46 |
| 305 | 13,17 | 36,84 |
| 306 | 13,21 | 32,77 |
| 307 | 13,29 | 30,38 |
| 308 | 13,40 | 29,14 |
| 309 | 13,55 | 28,77 |
| 310 | 13,74 | 29,20 |
| 311 | 13,98 | 30,56 |
| 312 | 14,28 | 33,27 |
| 313 | 14,64 | 38,04 |
| 314 | 15,07 | 38,24 |
| 315 | 15,59 | 31,93 |
| 316 | 16,21 | 27,63 |
| 317 | 16,95 | 24,76 |
| 318 | 17,82 | 22,82 |
| 319 | 18,85 | 21,56 |
| 320 | 20,07 | 20,88 |
| 321 | 21,50 | 20,71 |
| 322 | 23,07 | 21,07 |
| 323 | 24,41 | 22,00 |
| 324 | 24,74 | 23,60 |
| 325 | 23,53 | 26,11 |
| 326 | 21,49 | 29,88 |
| 327 | 19,34 | 34,05 |
| 328 | 17,39 | 32,37 |
| 329 | 15,68 | 28,71 |
| 330 | 14,18 | 26,42 |
| 331 | 12,86 | 25,22 |
| 332 | 11,68 | 24,66 |
| 333 | 10,62 | 24,22 |
| 334 | 9,65 | 23,32 |
| 335 | 8,75 | 21,83 |
| 336 | 7,92 | 20,17 |
| 337 | 7,15 | 18,79 |
| 338 | 6,43 | 17,90 |
| 339 | 5,76 | 17,61 |
| 340 | 5,15 | 18,02 |
| 341 | 4,58 | 19,27 |
| 342 | 4,06 | 21,67 |
| 343 | 3,58 | 25,81 |
| 344 | 3,14 | 30,26 |
| 345 | 2,74 | 26,59 |
| 346 | 2,36 | 22,83 |
| 347 | 2,02 | 21,14 |
| 348 | 1,70 | 21,28 |
| 349 | 1,41 | 23,52 |
| 350 | 1,15 | 26,23 |
| 351 | 0,92 | 20,27 |
| 352 | 0,72 | 14,32 |
| 353 | 0,54 | 10,12 |
| 354 | 0,39 | 7,03 |
| 355 | 0,26 | 4,68 |
| 356 | 0,16 | 2,91 |
| 357 | 0,09 | 1,60 |
| 358 | 0,03 | 0,70 |
| 359 | 0,01 | 0,17 |

**Antenna diagram 2**

| Gain (dB) | Horizontal aperture (°) | Vertical aperture (°) |
|---|---|---|
| 18 | 65 | 7 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 0 | 0,00 | 0,00 |
| 1 | 0,01 | 0,11 |
| 2 | 0,03 | 0,65 |
| 3 | 0,05 | 1,62 |
| 4 | 0,08 | 3,07 |
| 5 | 0,11 | 5,06 |
| 6 | 0,16 | 7,70 |
| 7 | 0,20 | 11,20 |
| 8 | 0,26 | 15,97 |
| 9 | 0,32 | 22,93 |
| 10 | 0,39 | 30,72 |
| 11 | 0,46 | 27,23 |
| 12 | 0,54 | 25,52 |
| 13 | 0,63 | 26,17 |
| 14 | 0,72 | 28,30 |
| 15 | 0,82 | 30,81 |
| 16 | 0,93 | 32,21 |
| 17 | 1,04 | 33,26 |
| 18 | 1,16 | 36,50 |
| 19 | 1,28 | 50,77 |
| 20 | 1,41 | 37,04 |
| 21 | 1,55 | 29,94 |
| 22 | 1,69 | 26,41 |
| 23 | 1,84 | 24,53 |
| 24 | 1,99 | 23,77 |
| 25 | 2,15 | 23,90 |
| 26 | 2,32 | 24,79 |
| 27 | 2,49 | 26,22 |
| 28 | 2,66 | 27,42 |
| 29 | 2,84 | 27,21 |
| 30 | 3,03 | 25,80 |
| 31 | 3,22 | 24,35 |
| 32 | 3,42 | 23,42 |
| 33 | 3,62 | 23,15 |
| 34 | 3,83 | 23,61 |
| 35 | 4,04 | 24,91 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 36 | 4,26 | 27,37 |
| 37 | 4,48 | 31,82 |
| 38 | 4,71 | 41,04 |
| 39 | 4,94 | 36,20 |
| 40 | 5,18 | 29,97 |
| 41 | 5,42 | 26,89 |
| 42 | 5,66 | 25,24 |
| 43 | 5,92 | 24,48 |
| 44 | 6,17 | 24,37 |
| 45 | 6,43 | 24,80 |
| 46 | 6,69 | 25,75 |
| 47 | 6,96 | 27,30 |
| 48 | 7,23 | 29,69 |
| 49 | 7,51 | 33,58 |
| 50 | 7,79 | 41,09 |
| 51 | 8,07 | 40,56 |
| 52 | 8,36 | 33,05 |
| 53 | 8,64 | 29,12 |
| 54 | 8,94 | 26,80 |
| 55 | 9,23 | 25,45 |
| 56 | 9,53 | 24,82 |
| 57 | 9,83 | 24,80 |
| 58 | 10,13 | 25,30 |
| 59 | 10,44 | 26,24 |
| 60 | 10,75 | 27,43 |
| 61 | 11,05 | 28,49 |
| 62 | 11,37 | 28,93 |
| 63 | 11,68 | 28,67 |
| 64 | 11,99 | 28,17 |
| 65 | 12,30 | 27,88 |
| 66 | 12,61 | 28,03 |
| 67 | 12,92 | 28,73 |
| 68 | 13,23 | 30,08 |
| 69 | 13,54 | 32,22 |
| 70 | 13,85 | 35,42 |
| 71 | 14,16 | 39,80 |
| 72 | 14,47 | 42,13 |
| 73 | 14,78 | 38,87 |
| 74 | 15,09 | 35,76 |
| 75 | 15,40 | 33,74 |
| 76 | 15,70 | 32,52 |
| 77 | 16,01 | 31,88 |
| 78 | 16,31 | 31,70 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 79 | 16,62 | 31,92 |
| 80 | 16,92 | 32,51 |
| 81 | 17,22 | 33,43 |
| 82 | 17,53 | 34,66 |
| 83 | 17,82 | 36,16 |
| 84 | 18,13 | 37,94 |
| 85 | 18,43 | 39,94 |
| 86 | 18,74 | 42,13 |
| 87 | 19,05 | 44,41 |
| 88 | 19,37 | 46,64 |
| 89 | 19,69 | 48,58 |
| 90 | 20,00 | 49,91 |
| 91 | 20,33 | 50,59 |
| 92 | 20,66 | 50,97 |
| 93 | 20,99 | 51,13 |
| 94 | 21,33 | 50,27 |
| 95 | 21,67 | 47,87 |
| 96 | 22,02 | 44,88 |
| 97 | 22,37 | 42,14 |
| 98 | 22,73 | 39,85 |
| 99 | 23,09 | 38,02 |
| 100 | 23,47 | 36,62 |
| 101 | 23,85 | 35,65 |
| 102 | 24,23 | 35,09 |
| 103 | 24,62 | 34,94 |
| 104 | 25,02 | 35,15 |
| 105 | 25,43 | 35,66 |
| 106 | 25,84 | 36,36 |
| 107 | 26,27 | 37,15 |
| 108 | 26,70 | 37,93 |
| 109 | 27,14 | 38,59 |
| 110 | 27,58 | 39,00 |
| 111 | 28,04 | 39,01 |
| 112 | 28,50 | 38,73 |
| 113 | 28,97 | 38,51 |
| 114 | 29,45 | 38,73 |
| 115 | 29,94 | 39,72 |
| 116 | 30,44 | 41,92 |
| 117 | 30,94 | 46,14 |
| 118 | 31,46 | 52,67 |
| 119 | 31,98 | 47,93 |
| 120 | 32,51 | 43,10 |
| 121 | 33,05 | 40,73 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 122 | 33,60 | 39,87 |
| 123 | 34,16 | 40,21 |
| 124 | 34,73 | 41,63 |
| 125 | 35,30 | 43,91 |
| 126 | 35,88 | 45,44 |
| 127 | 36,47 | 44,12 |
| 128 | 37,06 | 42,03 |
| 129 | 37,66 | 40,76 |
| 130 | 38,26 | 40,46 |
| 131 | 38,86 | 40,91 |
| 132 | 39,47 | 41,50 |
| 133 | 40,08 | 41,19 |
| 134 | 40,69 | 39,79 |
| 135 | 41,31 | 38,26 |
| 136 | 41,92 | 37,28 |
| 137 | 42,55 | 37,09 |
| 138 | 43,19 | 37,85 |
| 139 | 43,85 | 39,82 |
| 140 | 44,55 | 43,77 |
| 141 | 45,27 | 52,41 |
| 142 | 46,09 | 50,00 |
| 143 | 46,98 | 43,21 |
| 144 | 48,00 | 40,22 |
| 145 | 49,18 | 39,01 |
| 146 | 50,62 | 39,05 |
| 147 | 52,47 | 40,24 |
| 148 | 54,91 | 42,78 |
| 149 | 58,51 | 47,45 |
| 150 | 65,46 | 56,50 |
| 151 | 75,75 | 52,14 |
| 152 | 61,12 | 46,68 |
| 153 | 55,72 | 44,30 |
| 154 | 52,28 | 43,49 |
| 155 | 49,73 | 43,83 |
| 156 | 47,69 | 45,16 |
| 157 | 45,99 | 47,52 |
| 158 | 44,52 | 50,88 |
| 159 | 43,24 | 55,04 |
| 160 | 42,10 | 59,93 |
| 161 | 41,08 | 71,69 |
| 162 | 40,16 | 61,44 |
| 163 | 39,32 | 52,80 |
| 164 | 38,55 | 48,12 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 165 | 37,85 | 45,12 |
| 166 | 37,21 | 43,04 |
| 167 | 36,63 | 41,43 |
| 168 | 36,09 | 39,98 |
| 169 | 35,60 | 38,55 |
| 170 | 35,14 | 37,21 |
| 171 | 34,74 | 36,02 |
| 172 | 34,37 | 35,06 |
| 173 | 34,04 | 34,34 |
| 174 | 33,74 | 33,80 |
| 175 | 33,48 | 33,40 |
| 176 | 33,25 | 33,08 |
| 177 | 33,06 | 32,83 |
| 178 | 32,89 | 32,63 |
| 179 | 32,76 | 32,50 |
| 180 | 32,66 | 32,67 |
| 181 | 32,59 | 33,11 |
| 182 | 32,55 | 33,92 |
| 183 | 32,54 | 35,26 |
| 184 | 32,57 | 37,35 |
| 185 | 32,62 | 40,50 |
| 186 | 32,71 | 44,84 |
| 187 | 32,83 | 46,66 |
| 188 | 32,98 | 43,72 |
| 189 | 33,16 | 41,58 |
| 190 | 33,38 | 41,00 |
| 191 | 33,64 | 41,89 |
| 192 | 33,93 | 44,27 |
| 193 | 34,26 | 47,53 |
| 194 | 34,64 | 47,71 |
| 195 | 35,06 | 45,30 |
| 196 | 35,52 | 44,10 |
| 197 | 36,04 | 44,68 |
| 198 | 36,61 | 46,99 |
| 199 | 37,25 | 48,69 |
| 200 | 37,95 | 45,65 |
| 201 | 38,73 | 42,45 |
| 202 | 39,61 | 40,79 |
| 203 | 40,58 | 40,54 |
| 204 | 41,69 | 41,65 |
| 205 | 42,95 | 44,30 |
| 206 | 44,41 | 48,42 |
| 207 | 46,13 | 49,81 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 208 | 48,22 | 46,65 |
| 209 | 50,81 | 44,51 |
| 210 | 54,04 | 43,86 |
| 211 | 57,37 | 44,43 |
| 212 | 57,37 | 46,13 |
| 213 | 54,23 | 49,09 |
| 214 | 51,28 | 53,95 |
| 215 | 48,96 | 63,25 |
| 216 | 47,12 | 61,64 |
| 217 | 45,66 | 54,87 |
| 218 | 44,42 | 51,23 |
| 219 | 43,39 | 48,50 |
| 220 | 42,48 | 46,11 |
| 221 | 41,69 | 44,08 |
| 222 | 40,98 | 42,54 |
| 223 | 40,34 | 41,56 |
| 224 | 39,75 | 41,19 |
| 225 | 39,21 | 41,43 |
| 226 | 38,71 | 42,28 |
| 227 | 38,23 | 43,76 |
| 228 | 37,78 | 45,93 |
| 229 | 37,34 | 48,89 |
| 230 | 36,91 | 52,95 |
| 231 | 36,49 | 59,13 |
| 232 | 36,07 | 71,04 |
| 233 | 35,65 | 59,51 |
| 234 | 35,24 | 52,97 |
| 235 | 34,81 | 48,88 |
| 236 | 34,39 | 46,11 |
| 237 | 33,95 | 44,36 |
| 238 | 33,51 | 43,53 |
| 239 | 33,07 | 43,56 |
| 240 | 32,62 | 44,42 |
| 241 | 32,16 | 46,03 |
| 242 | 31,69 | 48,14 |
| 243 | 31,22 | 50,14 |
| 244 | 30,74 | 51,42 |
| 245 | 30,27 | 52,10 |
| 246 | 29,79 | 52,28 |
| 247 | 29,30 | 51,68 |
| 248 | 28,82 | 50,50 |
| 249 | 28,33 | 49,29 |
| 250 | 27,85 | 48,21 |

| Angle (°) | Attenuation (dB) | |
|---|---|---|
| | Horizontal | Vertical |
| 251 | 27,37 | 47,21 |
| 252 | 26,89 | 46,47 |
| 253 | 26,42 | 46,41 |
| 254 | 25,96 | 47,57 |
| 255 | 25,49 | 50,26 |
| 256 | 25,04 | 50,79 |
| 257 | 24,59 | 46,07 |
| 258 | 24,15 | 42,22 |
| 259 | 23,71 | 39,90 |
| 260 | 23,29 | 38,69 |
| 261 | 22,87 | 38,23 |
| 262 | 22,46 | 38,04 |
| 263 | 22,06 | 37,66 |
| 264 | 21,66 | 36,98 |
| 265 | 21,28 | 36,35 |
| 266 | 20,90 | 36,16 |
| 267 | 20,53 | 36,64 |
| 268 | 20,16 | 37,90 |
| 269 | 19,80 | 40,00 |
| 270 | 19,45 | 40,00 |
| 271 | 19,11 | 42,80 |
| 272 | 18,77 | 45,77 |
| 273 | 18,44 | 47,75 |
| 274 | 18,11 | 47,89 |
| 275 | 17,78 | 46,29 |
| 276 | 17,47 | 44,02 |
| 277 | 17,15 | 42,12 |
| 278 | 16,84 | 41,02 |
| 279 | 16,53 | 40,73 |
| 280 | 16,22 | 40,99 |
| 281 | 15,91 | 41,21 |
| 282 | 15,60 | 40,81 |
| 283 | 15,30 | 39,95 |
| 284 | 14,99 | 39,33 |
| 285 | 14,69 | 39,39 |
| 286 | 14,38 | 40,33 |
| 287 | 14,08 | 42,21 |
| 288 | 13,78 | 44,26 |
| 289 | 13,47 | 44,00 |
| 290 | 13,17 | 41,60 |
| 291 | 12,86 | 39,42 |
| 292 | 12,56 | 38,00 |
| 293 | 12,26 | 37,24 |
| 294 | 11,95 | 36,95 |
| 295 | 11,65 | 36,91 |
| 296 | 11,35 | 36,82 |
| 297 | 11,05 | 36,43 |
| 298 | 10,75 | 35,69 |
| 299 | 10,45 | 34,76 |
| 300 | 10,15 | 33,84 |
| 301 | 9,86 | 33,10 |
| 302 | 9,56 | 32,63 |
| 303 | 9,27 | 32,49 |
| 304 | 8,98 | 32,75 |
| 305 | 8,69 | 33,51 |
| 306 | 8,41 | 35,01 |
| 307 | 8,13 | 37,76 |
| 308 | 7,85 | 43,42 |
| 309 | 7,58 | 51,99 |
| 310 | 7,31 | 39,80 |
| 311 | 7,04 | 34,33 |
| 312 | 6,77 | 31,11 |
| 313 | 6,51 | 29,06 |
| 314 | 6,26 | 27,84 |
| 315 | 6,00 | 27,32 |
| 316 | 5,76 | 27,48 |
| 317 | 5,51 | 28,38 |
| 318 | 5,27 | 30,13 |
| 319 | 5,03 | 32,61 |
| 320 | 4,80 | 33,67 |
| 321 | 4,58 | 31,01 |
| 322 | 4,35 | 27,82 |
| 323 | 4,14 | 25,52 |
| 324 | 3,92 | 24,15 |
| 325 | 3,72 | 23,62 |
| 326 | 3,51 | 23,97 |
| 327 | 3,31 | 25,37 |
| 328 | 3,12 | 28,35 |
| 329 | 2,93 | 34,72 |
| 330 | 2,75 | 39,41 |
| 331 | 2,57 | 30,01 |
| 332 | 2,40 | 25,74 |
| 333 | 2,23 | 23,56 |
| 334 | 2,07 | 22,65 |
| 335 | 1,91 | 22,72 |
| 336 | 1,76 | 23,58 |
| 337 | 1,62 | 24,80 |
| 338 | 1,48 | 25,14 |
| 339 | 1,35 | 23,90 |
| 340 | 1,22 | 22,24 |
| 341 | 1,10 | 21,23 |
| 342 | 0,98 | 21,25 |
| 343 | 0,88 | 22,68 |
| 344 | 0,77 | 26,42 |
| 345 | 0,68 | 33,70 |
| 346 | 0,59 | 26,85 |
| 347 | 0,50 | 21,16 |
| 348 | 0,42 | 18,28 |
| 349 | 0,35 | 17,12 |
| 350 | 0,29 | 17,39 |
| 351 | 0,23 | 18,78 |
| 352 | 0,18 | 18,53 |
| 353 | 0,13 | 14,29 |
| 354 | 0,09 | 9,93 |
| 355 | 0,06 | 6,59 |
| 356 | 0,04 | 4,11 |
| 357 | 0,02 | 2,31 |
| 358 | 0,01 | 1,07 |
| 359 | 0,00 | 0,31 |

# Annex E: Change history

| Date | Version | Information about changes |
|---|---|---|
| July 2017 | 0.0.1 | Initial draft |
| December 2017 | 0.2.0 | Integration of agreements from July meeting and October review, integration of drafting sessions of November 2017 and December 2017 |
| January 2017 | 0.3.0 | Integration of RT #68 decisions |
| March 2018 | 0.4.0 | Integration of drafting session decisions:<br>- LTE channel location<br>- Results set 1<br>- Results set 3 |
| March 2018 | 0.5.0 | Added note and clarification on Worst Cell edge metric |
| April 2018 | 0.6.0 | Added section on comparison results |
| June 2018 | 0.7.0 | Interim conclusion with 1,4 MHz results |
| July 2018 | 0.9.2 | Clarifications on Fractional Frequency Reuse |

# History

| Document history | | |
|---|---|---|
| V1.1.1 | August 2018 | Publication |
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