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5G BROADCAST NETWORK PLANNING AND EVALUATION

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Abstract

The way in which the content and services of Public Service Media (PSM) organizations are delivered is evolving, particularly driven by the popularity of personal devices (smartphones, tablets) for accessing audiovisual (AV) media.

Whilst PSM content and services can be accessed on smartphones and tablets, this is only under conditions that do not comply with the fundamental requirements of PSM organizations. In particular, the need to deliver linear services free to air to all audiences, everywhere and at any time. This so-called universality principle lies at the core of the PSM remit.

Since the early 2000s, therefore, PSM organisations have tried to establish full access to such devices by including a broadcast receiver within them. All these attempts, which used different broadcast technologies – DVB-H, MediaFlo, ISDB-T Seg1, DVB-T2 Lite etc., have been unsuccessful.

The new technology called LTE-based 5G Terrestrial Broadcast (abbreviated to "5G Broadcast" in this report), developed and specified as part of the general mobile communication technology of 3GPP, is a broadcast mode of operation that seems to be a promising candidate for finally allowing all PSM services, both linear and nonlinear, to reach smartphones and tablets.

Many PSM organizations around the world are considering 5G Broadcast. However, before adopting this new technology it is crucial for PSM organisations to understand what the implications of such a decision would be. This refers to the potential and pitfalls of this new audio-visual distribution option in terms of technology, regulatory constraints and business implications. This report sheds some light on the network planning of 5G Broadcast. The frequency planning of 5G Broadcast, including sharing and compatibility between 5G Broadcast and other DTT systems in the spectrum range 470 – 694 MHz is dealt with in a separate EBU Technical Report, TR 064.

Extensive studies have been carried out. Both theoretical (i.e. regular gridded) networks, and real-world network topologies have been investigated, based on sets of scenarios and related technical parameters (as described in this report and its Annexes). One aim of these studies is to address whether broadcasting infrastructure, including High Power High Tower and Medium Power Medium Tower could be employed to provide 5G Broadcast services to Car-Mounted and Handheld Portable receivers.

Information on the status of 5G standardization, including 5G Broadcast, and deployment opportunities can be found in EBU Technical Report TR 054 "5G for the Distribution of Audiovisual Media content and services".

The main findings of the studies carried out of this report can be summarised as follows:

1. All 'Homogeneous'[1] network topologies based on using only one type of site (HPHT, MPMT or LPLT)[2] have drawbacks when considered separately for 5G Broadcast coverage. HPHT or MPMT alone offer good coverage for Fixed roof-top with low site density but do not provide good coverage for Mobile reception in all environments. On the other hand, LPLT

[1] Homogeneous means that only one type of site is used in the network.

[2] HPHT: High Power High Tower networks

MPMT: Medium Power Medium Tower networks

LPLT: Low Power Low Tower networks

The characteristics of these networks are defined in Annex A.

alone provides good coverage for Mobile (as well as for Handheld and Fixed) in all environments but requires high site density.

2. Hybrid networks including three layers of HPHT, MPMT and LPLT offer the best compromise between good coverage for mobile and reasonable site density. The word Hybrid here is not a simple mixture of sites but true three-layer networks, with HPHT sites serving as umbrella, complemented underneath by MPMT sites in some rural and suburban areas, which are complemented underneath by LPLT sites in urban areas.

3. Such hybrid topologies can provide sufficiently high SINR levels (up to 15 dB) to allow the use of efficient 5G Broadcast Modulation and Coding Schemes reaching throughputs of up to 7 Mbit/s in 5 MHz, in Mobile and handheld reception conditions.

4. The use of the same frequency and the same editorial content in SFN mode between all sites and layers offers the best performance, thanks to the gain offered by such networks. However, Single Frequency Networks (SFNs) may not be implementable over very large areas due to editorial content change across borders, and to the current interleaved use of spectrum for DTT imposed by the Geneva 2006 Agreement (GE06). Therefore, a mixture of MFN and SFN would be required, within the constraints of GE06. Future studies may investigate closed SFNs[3] using the same frequency across border areas to mitigate the need for MFN.

5. Trials are needed to verify the conclusions and the assumptions of the studies. Future studies should consider enhancement techniques for mobile reception, such as time interleaving.

[3] A Closed SFN uses directional antenna patterns at transmitters located at its edge, oriented towards the centre of the SFN, to reduce the outgoing interference to neighbouring co-channel networks.

List of Acronyms and Abbreviations

The following terms are used throughout this report:

Abbreviation / Acronym	Expansion
3GPP	3rd Generation Partnership Project
BNO	Broadcast Network Operator
BW	Bandwidth
CAS	Cell Acquisition Subframe
CDF	Cumulative Distribution Function
CE	Channel Estimation
C/I	Carrier to interferer ratio
C/N	Carrier to noise ratio
CM	Car Mounted
CP	Cyclic prefix (mobile term) - equivalent to Guard Interval (broadcast term)
DAB	Digital Audio Broadcasting
DTM	Digital Terrain Model
DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
DVB-H	Digital Video Broadcasting — Hand held
DVB-T	Digital Video Broadcasting — First Generation Terrestrial
DVB-T2	Digital Video Broadcasting — Second Generation Terrestrial
EIRP	Equivalent Isotropically Radiated Power
ERP	Equivalent (or Effective) Radiated Power
eMBMS	Evolved Multimedia Broadcast Multicast Services
FeMBMS	Further Evolved Multimedia Broadcast Multicast Services
FFT	Fast Fourier Transform
GE06	Geneva Agreement 2006
GI	Guard Interval
HH	Handheld
HPHT	High-Power High-Tower
ICI	Inter Carrier Interference
ISD	Inter-Site Distance
ISDB-T 1 seg	Integrated Services Digital Broadcasting -- Terrestrial for handheld mobile reception
ITU	International Telecommunication Union
LPLT	Low-Power Low-Tower
LTE	Long Term Evolution
LTE-B / MediaFlo	Qualcomm proprietary broadcast system aimed at handheld reception
MCS	Modulation and Coding Scheme
MFN	Multi Frequency Network
MNO	Mobile Network Operator

Abbreviation / Acronym	Expansion
MPMT	Medium-Power Medium-Tower
OFDM	Orthogonal Frequency-Division Multiplexing
PMCH	Physical Multicast Channel
PO	Portable Outdoor
PSM	Public Service Media
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature phase shift keying
RB	Resource block
SFN	Single Frequency Network
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio

Contents

5G Broadcast Network Planning and Evaluation

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Keywords: PSM, Broadcast, Audiovisual Media, LTE-based 5G Terrestrial Broadcast, 5G Broadcast, Network Coverage, Network Capacity.

1. Theoretical Network model and simulation results

1.1 Introduction

Theoretical network simulations are based on repeated regular hexagonal networks, where the central hexagon in the network is considered as the area of interest. Within this area of interest, signal to noise ratio (SNR) and signal to interference plus noise ratio (SINR) are derived for a set of locations, considering different network topologies, frequency reuse patterns and reception conditions. The resulting SNR and SINR values for these locations help to build a view on the pairing of network topologies and reception modes.

Sections 1.2 to 1.4 give an overview of the parameters and assumptions taken into account in the simulations. § 1.5 demonstrates the issue of coverage in national or regional border areas with reuse 1. The main body of results of the theoretical network simulations are presented in § 1.6 along with observations and related summaries. § 1.7 provides analysis of two specific issues: the impact of practical antenna pattern and the Doppler performance requirements for mobile reception. § 1.8 deals with the mapping between channel capacity and SINR.

Finally, § 1.9 provides conclusions from simulation results on theoretical Networks.

The whole set of results presented in this report is based on a 5G Broadcast system using a 5 MHz wide channel at 600 MHz. As can be seen in EBU Technical Report TR064 [1], a 5 MHz wide channel is not the most efficient use of an 8 MHz GE06 channel, but for the time being, the use of an existing 3GPP channel raster can ensure compatibility with existing broadcast services using GE06 channel arrangements. Furthermore, if a new channel raster is standardized at the 3GPP level and provided that the relevant network topologies are adapted (maintaining a constant radiated power per MHz, as is done in the correction table in Annex A (Table A6), the results presented here will remain valid for this new raster.

1.2 Network topologies and frequency reuse

The setup of the simulations typically relies on regular hexagonal networks. Several approaches are taken to establish these hexagonal networks, both in terms of geometry and possible frequency assignment.

Regarding geometry, two options are considered:

Option 1: Homogenous Network

- Option 1 is quite straightforward, using homogeneous networks to establish a layer of sites located on a regular grid on the area of interest, as shown on Figure 1 below.
  - The geometry of a set of standard network topologies was defined based on a review of real operating networks.
  - These topologies and their associated parameters, described in detail in § A4 in Annex A, are split in the three traditional categories: High Power High Tower (HPHT), Medium Power Medium Tower (MPMT) and Low Power Low Tower (LPLT).
  - The choice of one category and a set of associated parameters, allows one to completely define the network parameters to be used for one simulation: inter-site distance (ISD), transmitter EIRP and antenna height, transmitting antenna characteristics. On this last item, while a vertical radiation pattern might be considered for some categories, an omnidirectional pattern is assumed in the horizontal plane, unless stated otherwise.

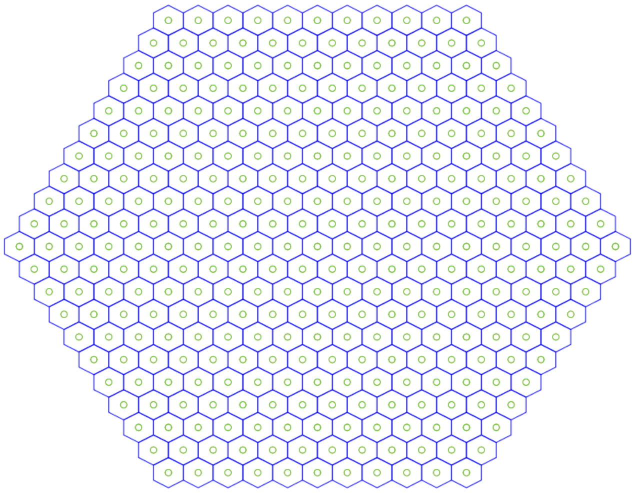


Figure 1: Homogeneous network layout (green dot: site, blue line: cell extent)

  - The choice of one category and, in particular, the associated ISD is a dimensioning factor in terms of network deployment cost. The relationship between the ISD and the site density is shown in Table 1: in general, the denser the network used to cover a given area, the higher are the associated deployment and running costs.

Table 1: Relationship between the ISD and the site density (see Note below the table)

ISD (km)	Cell area (km²)	Site Density / 10000 km²	Site density ratio wrt 80 km ISD
3	7.79	1283.0	711.1
12	124.71	80.2	44.4
20	346.41	28.9	16.0
50	2165.06	4.6	2.6
80	5542.56	1.8	1.0
100	8660.25	1.2	0.6
120	12470.77	0.8	0.4
150	19485.57	0.5	0.3

Note: The site density ratio is based on the ISD of 80 km for HPHT used for the simulations results found in this report.

Option 2: Hybrid Network

- Option 2 simulates real world deployments for broadcast networks, where a mix of topologies is found, generally between HPHT and MPMT sites. This approach is called “Hybrid” to reflect the mix of topologies, and relies on the following principles (an example of the application of these principles can be seen in Figure 2 below):
  - One main layer with a regular homogeneous network is first selected.
  - One secondary layer defines a regular homogeneous network with a smaller ISD than in the main layer.
  - Each layer has its own transmitter parameters (transmitter EIRP, antenna height, antenna characteristics) defined independently of the other layer.
  - The arrangement of the main layer topology is based on the choice of a specific ISD.
  - The arrangement of the secondary layer topology is based on the main layer topology, to end up with a regular arrangement between main and secondary layer sites:
    - Secondary layer sites are positioned along each edge of the main layer cells.
    - Each edge of the main layer cells is divided in a certain number of parts, which define the number of secondary layer cells per edge.
    - Additional secondary layer cells are generated along the first set of cells created previously, leaving sparse areas around the main layer sites.

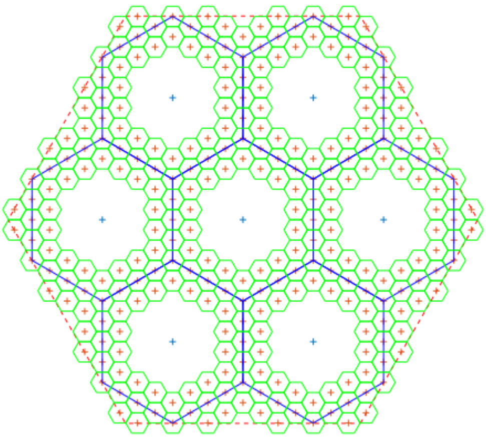


Figure 2: Hybrid network layout (blue cross/line: main layer site/cell, red cross: secondary layer site, green line: secondary layer cell)

  - The aim of the secondary layer is to bring a reinforced signal in the weakest areas of the main layer.

Once the geometry is defined, the frequency assigned to each cell in the network plays an important role in the assessment of the performance:

- For both homogeneous and hybrid cases, it is possible to use a classical frequency reuse scheme:
  - Either frequency reuse 1 [4], i.e., all sites in the network use the same frequency. In addition, it is considered in this case that all the sites are part of the same SFN, transmitting the same content in synchronisation.

[4] In this report reuse 1 is:

- SFN inside the same editorial region (could be a full country or parts of a country for regional content)

  - Either frequency reuse 3 or 4, as depicted in the figure below. In this case a pure Multiple Frequency Network (MFN) approach is considered, i.e., each site is potentially transmitting a different content with no synchronisation constraint of any sort.

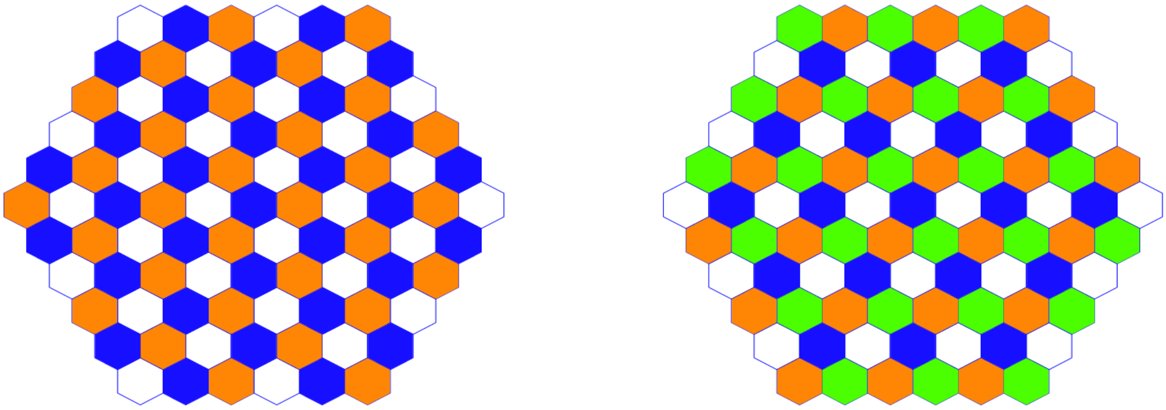


Figure 3: Frequency reuse 3 (left) and 4 (right)
Each colour represents a different frequency assignment

  - The application of reuse 1 is straightforward for homogeneous and hybrid cases; the application of reuse 3 and 4 is also straightforward for homogeneous cases. In the case of hybrid networks, the application of reuse 3 or 4 is primarily done on the main layer; then, every site of the secondary layer which falls inside a cell of the main layer is assigned the same frequency as this main layer cell (secondary layer cells at the edge of primary layer cells can get two or three simultaneous frequency assignments, which is not a problem as only one frequency is analysed in this case, see § 1.4), and assumed to form a SFN with the main layer cell they correspond to.

- In addition, for homogeneous cases, a mixed approach can be used for frequency assignment: the mix is between MFN and SFN situations, i.e., MFN clusters of SFNs can be considered, the MFN clusters adopting a frequency reuse 3 or 4, and all sites belonging to the cluster forming the same SFN (with the same content transmitted in sync), as can be found in some operational broadcast deployments. This approach provides a middle ground between a full SFN situation and a full MFN situation for a given network topology. To preserve the regularity characteristics of the original network topology, the clusters are formed from regular assemblies of sites: 7, 19, 37, …

  Furthermore, to limit the extent of each cluster, the size of the clusters can be constrained depending on the original network topology, e.g. only clusters of 7 sites for HPHT topology, clusters of 7 or 19 sites for MPMT topology and clusters of 7, 19 or 37 sites for LPLT topology.

The figure below illustrates such clustering approaches in the case of frequency reuse 3 between the clusters, showing only the clusters on the same frequency (clusters with red dots) as the central cluster (cluster with green dots).

- Co-channel between two different regions (across regional borders inside a country or across national border between two countries)

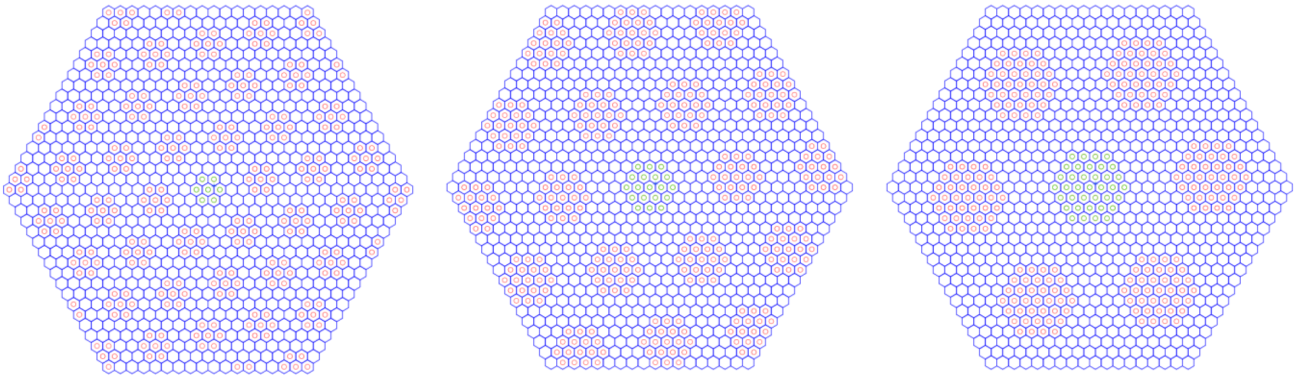


Figure 4: Example of Reuse 3 MFN clusters of SFNs – Only the co channel clusters are shown (left to right: 7 sites cluster, 19 sites cluster, 37 sites cluster)

As can be seen in § A4 in Annex A, a limited set of possible parameters is defined for each network topology. However, when combined with the other variables in the simulation (choice of homogeneous / hybrid network, frequency assignment and reception mode), this gives a potential of thousands of scenarios to explore. To make it possible to have a complete view on the performance of selected networks topologies and parameters to serve the various reception modes identified, only a subset of those thousands of possibilities was considered during the work associated with this report. The corresponding parameters associated with the selected scenarios and the corresponding results are described in § 1.6.

1.3 Reception modes and parameters

For the assessment of the various network topologies and frequency reuse patterns defined in § 1.2 above, six reception modes are considered appropriate:

- Car Mounted reception,
- Handheld In car reception,
- Handheld Portable Outdoor reception
- Portable Indoor reception
- Handheld Portable Indoor reception
- Fixed reception

For each reception mode, the detailed characteristics of the receiver are defined: receiving antenna height, antenna gain, receiver noise figure etc. These detailed characteristics can be found in § A3 in Annex A. For Fixed reception, a directional receiving antenna (using ITU-R P.419-3 diagram) is considered, while for all other reception modes, a purely omnidirectional receiving antenna is considered. No polarisation discrimination is taken into account in this analysis, as the receiver is assumed to use the same polarisation as the transmitters, which are all using the same polarisation.

For the specific case of SFN reception, i.e., when several signals from the same SFN are received and need to be considered, the receiver is assumed to use a maximum C/I synchronization strategy (as defined in EBU Technical Review 295 [10]) which is an optimal strategy. In this case, the windowing function used to split the signals between useful and interfering parts inside the SFN is the function defined in § 3.5 of EBU Tech 3348 [2] using the 5G Broadcast system parameters from Table A1 (Annex A).

Regarding the propagation model, ITU R Recommendation P.1546 5 is used to predict wanted and interfering field strengths from the various transmitters to the locations considered in the simulations. As indicated in § A1 in Annex A, wanted signals are predicted for 50% of time, while unwanted signals are predicted either using 1.75% of time (for location variation only simulations) or any suitable percentage of time (for location and time variation simulations) as described in § 1.4.

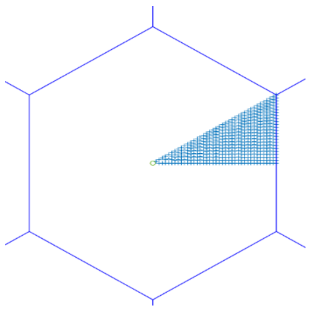
1.4 Simulation methodology

The selection of parameters for a given network topology, the frequency reuse pattern (as described in § 1.2) and the reception mode (as described in § 1.3) form a complete scenario to be considered in a simulation run.

Whatever the simulation is, it is always based on the central "cell" of the network using a Monte Carlo algorithm on a set of reception locations within this central cell:

- In the case of homogeneous networks with conventional reuse 1, 3 or 4, this cell is the central cell of the network
- In the case of homogeneous networks with MFN clusters of SFNs, this cell corresponds to the set of cells forming the central cluster
- In the case of hybrid networks, this cell corresponds to the central cell of the main layer

This set of reception locations is derived from the central cell using a regular grid. Whenever possible, symmetry axes are used to reduce the number of such reception locations and speed up computations.



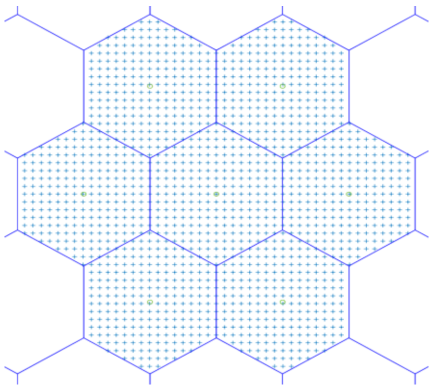


Figure 5: Examples of central cell sampling – Reception locations indicated as '+'
Left: using symmetries (homogeneous networks with conventional reuse, hybrid networks)
Right: not using symmetries (homogeneous networks with MFN clusters of SFNs)

Each reception location is considered to form a small area of coverage of the network, the size of which depends on the network topology[5] as follows, due to computation time and memory constraints limits linked to the inter site distance / central cell area:

- HPHT topology: small area of 500 m x 500 m (general case) or 1000 m x 1000 m (for MFN clusters of SFNs)

[5] In the case of hybrid networks, the topology to consider is the one of the main layer.

- MPMT topology: small area of 250 m x 250 m (general case) or 500 m x 500 m (for MFN clusters of SFNs)
- LPLT topology for rural environments: small area of 150 m x 150 m or 250 m x 250 m (general case) or 500 m x 500 m (for MFN clusters of SFNs)
- LPLT topology for urban/suburban environments: small area of 50 m x 50 m (general case) or 100 m x 100 m (for MFN clusters of SFNs).

At each reception location, a Monte Carlo algorithm is applied to derive SNR and SINR values for the reception location and for a given percentage of locations (over the small area it represents) and percentage of time (usually taken as 95% of locations / 99% of time respectively for broadcast requirements). Two simulators were developed to achieve this computation:

- The first simulator does a unique Monte Carlo loop to derive statistics regarding location variation only[6] , introducing time variation aspects through the prediction model (wanted signals are predicted for 50% of time, unwanted signals are predicted for 1.75% of time following the advice by ITU-R Working Party 3K prescribed in the “Simple method” of ITU Document 6A/198 [11] that individual interfering field strength computed using Recommendation ITU-R P.1546-5 at 1.75% of time reflects the real correlation situation of interfering field strength and correspond to 1% of time for the aggregated field strength.).
- The second simulator uses two nested Monte Carlo loops to derive statistics for location variation and time variation of signals[7]. This produces a more consistent behaviour in predictions regarding the wanted and unwanted parts of signal originating from a given source in SFNs, though at the expense of a much-increased computation time due to the nested Monte Carlo loops. This simulator has not been used for the derivation of the results shown in § 1.6 below due to the excess runtime.
- The two simulators can examine both the data part (useful payload carried by the Physical Multicast Channel – PMCH – of the 5G Broadcast system) and the signalling part (CAS – Cell Acquisition Subframe), but the current simulations were only run on the data part, considering that the signalling part is not a limiting factor in the effective reception of the signal[8] .

The location variation only Monte Carlo algorithm is applied at each reception location as follows:

1. Compute the median wanted and unwanted signal levels from each site at the reception location taking into account transmitter and receiver characteristics. Only signals originating from sites on the same frequency as the central cell are taken account of in this computation, since adjacent channel interference plays a secondary role.
2. For each location (Monte Carlo loop with N iterations, N taken as 10000 in the simulations).
   a. Compute the shadowing factor (based on the applicable location standard deviation) for each site.[9]

[6] Simulator code available, on request for access, from https://git.ebu.io/smr-sdb/embms-simulations.

[7] Simulator code available, on request for access, from https://git.ebu.io/smr-sdb/embms-simulations-time.

[8] Despite its robustness, the CAS signal can only use the legacy LTE numerology (15 kHz with normal cyclic prefix, i.e., Tu = 66.67 µs, CP = 4.7 µs). This may have in impact on SFN reception, due to the very short CP duration, depending on the behaviour of the receiver.

[9] The shadowing factors are assumed to be uncorrelated between the sites. In some cellular network simulations, an autocorrelation of the shadowing factors is indicated. This is not considered here.

b. Correct the wanted / unwanted levels from each site with the corresponding shadowing factor.

c. In case of SFN reception (reuse 1 or MFN clusters of SFN), apply the synchronisation strategy[10] to the signals originating from the sites in the SFN to derive wanted and unwanted intra SFN signals.

d. Sum (using simple power sum) the wanted intra SFN signals and the unwanted (intra SFN and out of SFN) signals separately to derive the SNR and SINR values for the current location instance.

e. Accumulate each SNR and SINR location instance value in a table.

3. Once the Monte Carlo loop is over, derive a CDF of SNR and a CDF of SINR from the accumulated values, and apply the location threshold (usually 95%) to derive the SNR and SINR values reached for at least this percentage of locations, on the current reception location.

Repeating the previous procedure over the whole set of reception locations allows a surface analysis to be built, with charts showing coverage area versus specific available SNR and SINR values at the wanted percentage of locations.

The following figures show an example of the application of such a procedure for a homogeneous network simulation: Figure 6 shows the resulting computed SINR values for all reception locations considered across a central cell, in the form of a heat map (reconstructed thanks to symmetries when symmetries are used to derive the set of reception locations, using the original set of reception locations otherwise); based on these values, and selecting relevant SINR values, one can also derive a histogram representing the relative area covered for a given set of SINR values, as shown in Figure 7.

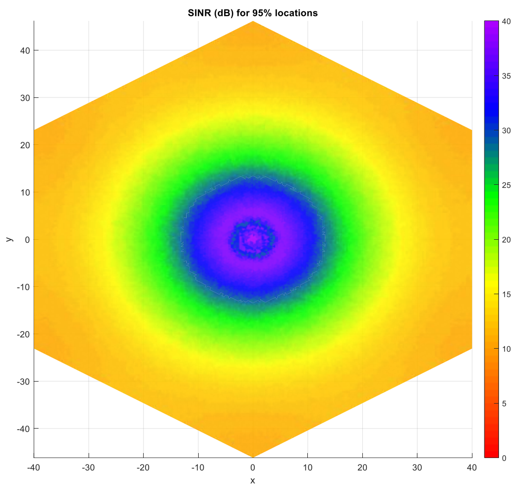


Figure 6: Computed SINR values for 95% of locations at reception locations across a central cell

Accumulating the resulting histogram of different scenarios (e.g., change in reuse factor, usage of MFN clusters of SFNs, …) allows a performance comparison of the different scenarios to be made.

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[10] As theoretical networks are considered here, all transmitters in the SFN network are assumed to have an initial static delay set to 0 µs.

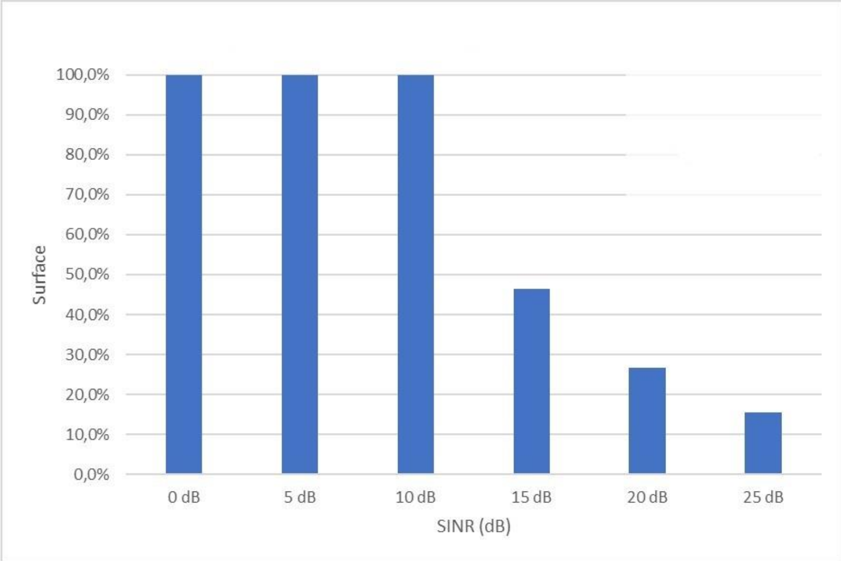


Figure 7: Sample histogram resulting from the previous SINR computation, for outstanding SINR values

The location and time variation Monte Carlo algorithm embeds the previous procedure in a time instance loop and replaces the wanted / unwanted signal level generation by a generation for a given time instance value.

The SNR and SINR values are accumulated along two dimensions and need two thresholding procedures to derive the SNR and SINR values reached for the targeted time and location percentages on each reception location (as already said, usually 99% of time / 95% of locations). The location and time variation Monte Carlo algorithm is applied as follows at each reception location, since location variation and time variation are independent random variables:

1. Generate M (number of Monte Carlo trials for the time variation; M was taken as 10000 in the simulations) time instances for each transmitting site. The generation of those time instances is based on the “General method” described in ITU Document 6A/198 [11], using an extended version of Recommendation ITU-R P.1546-5 in the time domain, and α=1.

2. Generate N (number of Monte Carlo trials for the location variation; N was taken as 10000 in the simulations) shadowing components - i.e., location instances - for each transmitting site (those trials are generated in the same way as for the location variation only simulator).

3. For each time instance;

    a. For each location instance;

        i. Compute the received field strength from each transmitting site (only for the sites on the same frequency as the central cell) at the current receiving location, considering its time / location instances and the receiver characteristics.

        ii. Derive the corresponding SINR (taking into account SFN self-interference when needed and/or co channel interference when applicable) and store it in a matrix.

4. Using the SINR matrix;

    a. Derive the CDF of SINR with respect to location, considering the target time percentage. From this, derive the available SINR considering the target location percentage.

b. Derive the CDF of SINR with respect to location, considering the target location percentage. From this, derive the available SINR considering the target time percentage.

The application of steps 4a and 4b should, in principle, return the same SINR value for the target time and location percentages. However, due to the nesting of time and location loops in steps 1 to 3, reaching the same value is not guaranteed, considering the currently "reduced" number of trials in both dimensions (nested Monte Carlo simulations usually require many loops in each dimension to reach a stable result).

In practice, less than 0.5 dB difference was observed for the limited set of simulations that were done using the location and time variation Monte Carlo algorithm. Decreasing this difference would require significantly increasing the number of trials in both dimensions, putting an increased pressure on runtime and memory usage (possibly even exhausting memory due to the necessary storage of the time / location SINR matrix, unless specific measures are taken).

Using this algorithm provides a more optimistic result in terms of available SINR; for one given time instance, the wanted and unwanted signals from one transmitting site are predicted using the exact same percentage of time value using Recommendation ITU-R P.1546-5, hence producing a physically consistent situation (rather than an artificial 50% of time for wanted signal and 1.75% of time for unwanted signal from the same transmitting site).

The aggregation of the whole set of time instances generally results in a higher SINR on the considered reception location. Of the limited set of simulations that was done, improvement in SINR at the worst location was in the range of 1.5 – 3 dB for Fixed reception with reuse 1, depending on the topology, and less than 0.2 dB for portable reception with reuse 1.

As this was done in the early stages of the work, further assessment would be necessary to fully qualify the difference resulting from using the location and time variation Monte Carlo algorithm compared with the location only Monte Carlo algorithm, in particular over the whole coverage area and not only at the worst location. For the time being, and as previously explained, the results presented in the following sections are based on the location variation only Monte Carlo algorithm.

1.5 Coverage of national or regional border areas

1.5.1 Background

This section shows the impact of single frequency operation across regional or national boundaries with different content in each region.

This topic was studied as part of work associated with CEPT TG6, in around 2013, which explored the impact of single frequency use across regional boundaries primarily for Fixed reception [12]. At that time, it was shown that it was not possible to operate reuse 1 networks in border areas and provide complete coverage for Fixed reception.

As the TG6 work only considered Fixed reception, similar work has been done in this section to cover some of the scenarios being considered as part of the 5G Broadcast studies; namely,

- HPHT, MPMT and LPLT network structures
- Mobile (Car Mounted) reception

For the above scenarios, the reduction in availability (coverage) in cells adjacent or close to the border was investigated for single frequency operation across a regional or national boundary with different content in each region. In line with the approach taken in the TG6 work, the impact on cells/sectors, adjacent or near to a border has been assessed.

The case where an area is partly enveloped by a different region has been modelled. This has been represented by dividing the modelled area into 4 quadrants. Of these quadrants, 3 represent interfering regions and the fourth (lower left) is the wanted region. (see Figure 9a below and §§ C1.1, C2.1 and C3.1 in Annex C). In this situation, a wanted cell has interfering cells adjacent on 4 faces. The impact has been reported as a CDF of the SINR available across the area and a heat map of available SINR.

In addition, the case where a regional boundary is straight has been modelled with two sub cases: Vertical North South boundary (see §§ C1.3, C2.3 and C3.3 of Annex C) and Horizontal East West boundary (see §§ C1.2, C2.2 and C3.2 of Annex C). As we are working with networks based on hexagonal cells there is a slight difference in interference between the two cases - one has an interfering cell adjacent on 3 faces of the hexagon, the other an interfering cell on two faces.

1.5.2 Results

Example results are provided in Figures 8 & 9. The full set of results for the three different network topologies, Car Mounted (i.e. mobile) reception and a 5 MHz bandwidth are provided in Annex C.

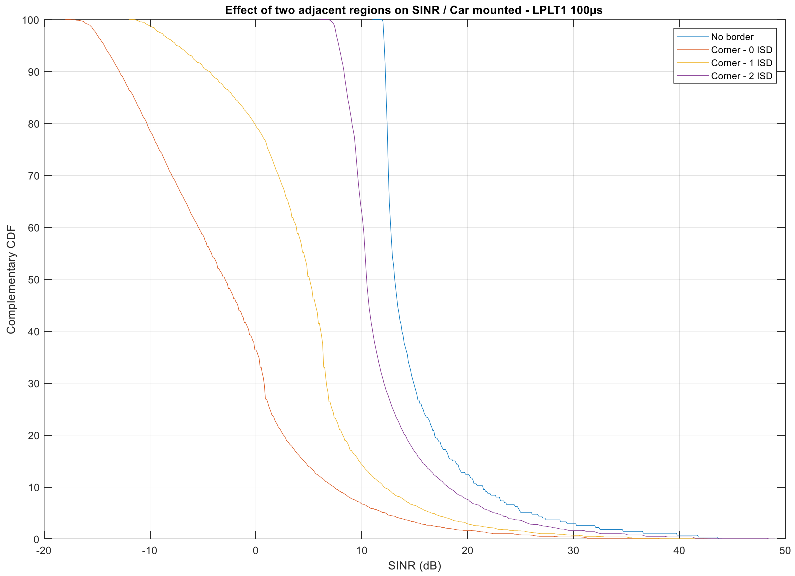


Figure 8: CDF for LPLT - corner regional boundary

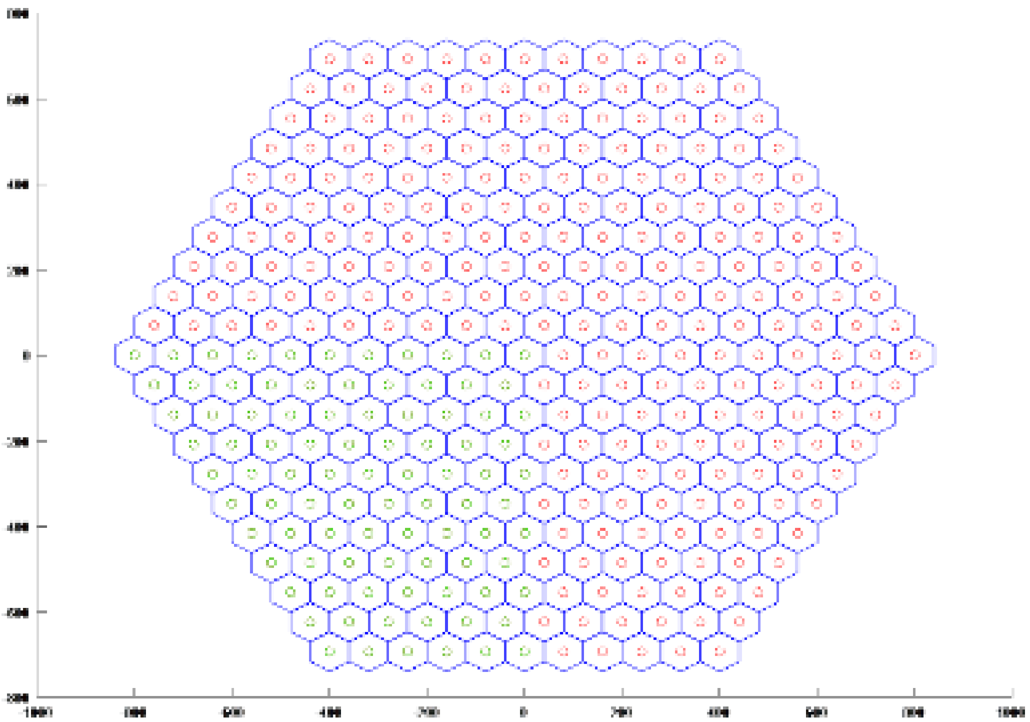


Figure 9a: Network Geometry corner (the green cells are the wanted region, red cells are the interfering region. The assessed cell is the central cell)

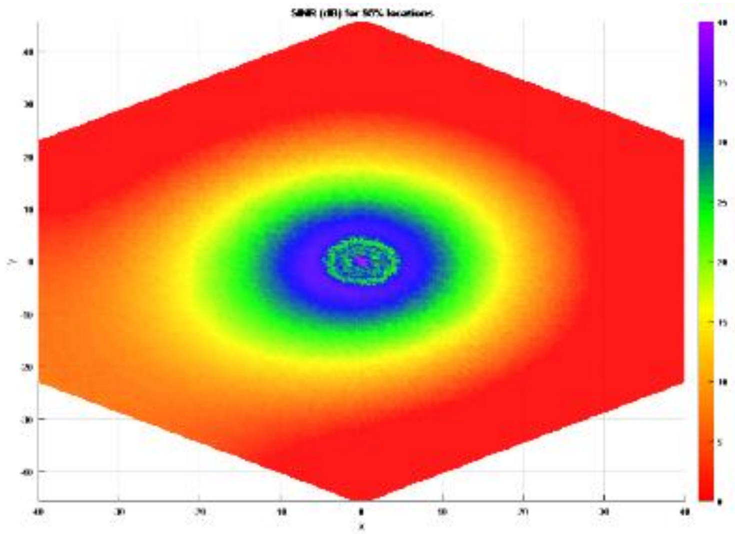


Figure 9b: Resulting SINR heat map for HPHT case

1.5.3 Discussion

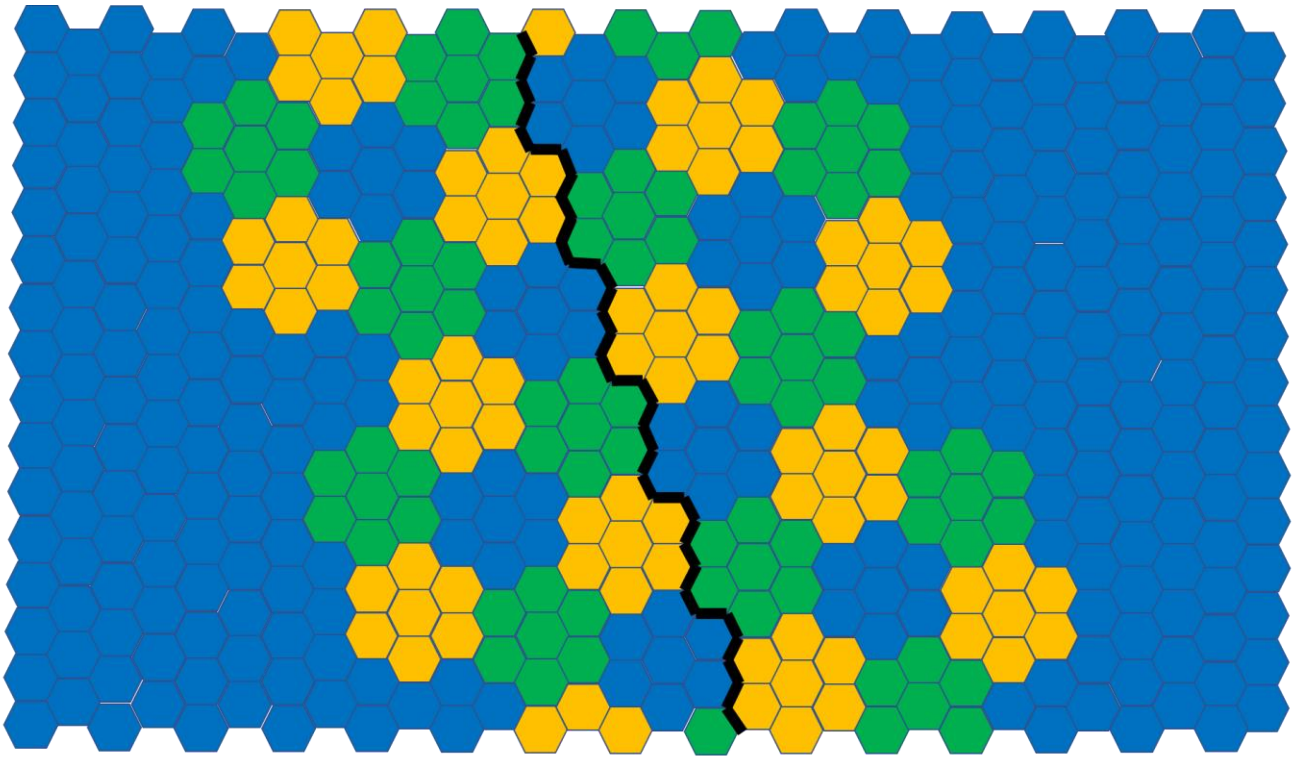
The results (Annex C) show that for all network topologies, HPHT, MPMT & LPLT, coverage in border areas is reduced when compared with coverage away from the border. Coverage is compromised in a band running along the border.

- For HPHT networks, the first and second cells from the border are mainly impacted, while the third cell suffers almost no impact on its coverage as part of a reuse 1 national network. In terms of distance from the border, this represents roughly 2x ISD (Inter-site Distance of the HPHT network). For an ISD of 80 km, most considered in the current simulations, this represents 160 km. This order of distance would still allow a reuse 1 inside, but not across the whole territory of, a large country (France, Germany, Spain, Poland, etc.) but not in small countries (Luxembourg, Belgium, Croatia, etc.)

- For MPMT and LPLT networks, the first, second and third cells from the border are impacted. The impact is expected to be minimal on the fourth cell. In terms of distance from the border, this represents 3x ISD. For an MPMT ISD of 20 km, this represents 60 km from the border. For an LPLT ISD of 12 km, this represents 36 km. These distances are sufficiently low for medium size countries to allow some reuse 1 inside their territories.

A straightforward solution in such border areas is to use different frequencies for SFNs that transmit different content (across national or regional borders). For LPLT and MPMT this probably means a frequency reuse of 3 is required. Figure 10 shows an illustration of using MFN with reuse 3 on both sides of a border while still using SFN inside each area at a distance from the border. For HPHT, given the ISD, a frequency reuse of 4 would be required when regions or countries are comparable in size to the coverage area of a station.

It may be possible to reduce the size of the impacted area by implementing closed SFNs[11]. This has not been investigated but it is believed that while it would reduce the size of the impacted area, it would not entirely eliminate the problem.



[11] A Closed SFN uses directional antenna patterns at transmitters located at its edge, oriented towards the centre of the SFN, to reduce the outgoing interference to neighbouring co-channel networks.

Figure 10: Illustration of an MFN at the border area with reuse 3 while SFN is used inside each country at a distance from the border

1.5.4 Conclusion

Regardless of the network configuration it is not possible to operate reuse 1 networks in border areas and provide contiguous coverage. In border areas, full coverage requires either a higher frequency reuse, i.e., to use Multiple Frequency Networks (MFN) in the concerned border areas, or a solution to reduce the size of co channel interference by implementing closed SFNs.

1.6 Results

The full set of detailed results can be requested from the EBU ([5G planning simulation results]). The following provides analysis for each use case (Car Mounted, Handheld Portable outdoor, Handheld In-Car and Fixed reception).

1.6.1 Networks assessment for Car-Mounted reception

Effect of the Cyclic Prefix and the frequency reuse on the coverage

Figures 11 & 12 show the percentage of surface covered for different target SINR values for Car Mounted reception using HPHT with 300 µs cyclic prefix (CP) and 200 µs CP respectively (see Table A1 for the different possibilities offered by 5G Broadcast).

Figures 13 & 14 show the same type of results but using MPMT. The main characteristics of these homogeneous networks are shown in Table 2.

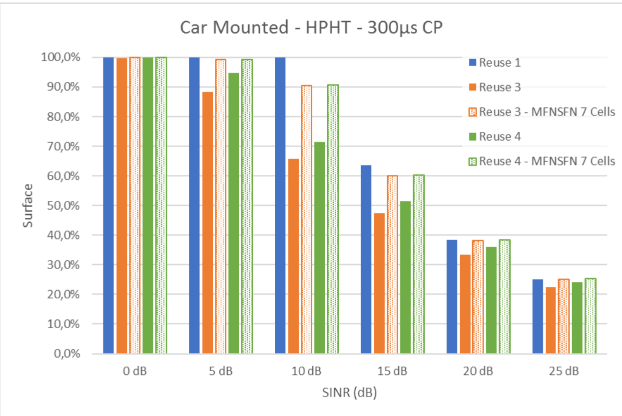


Figure 11

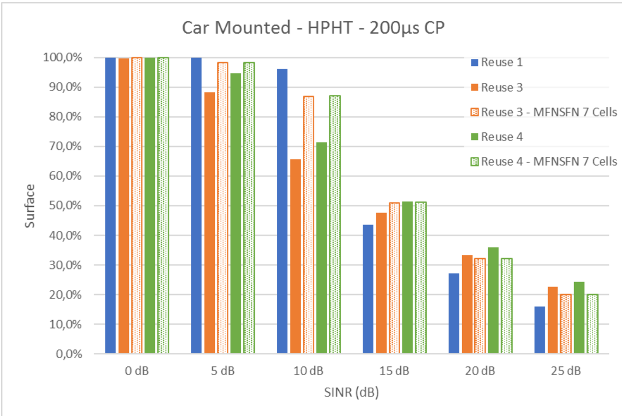
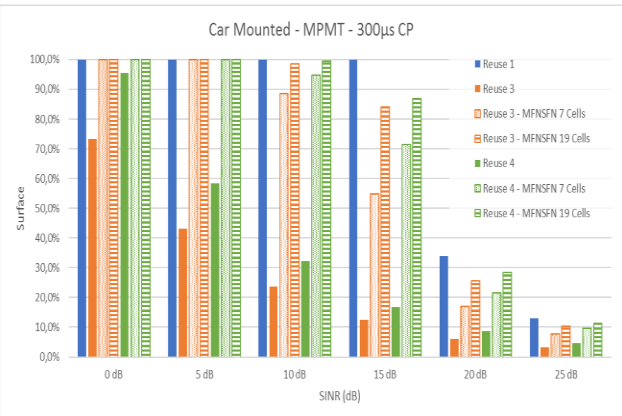


Figure 12



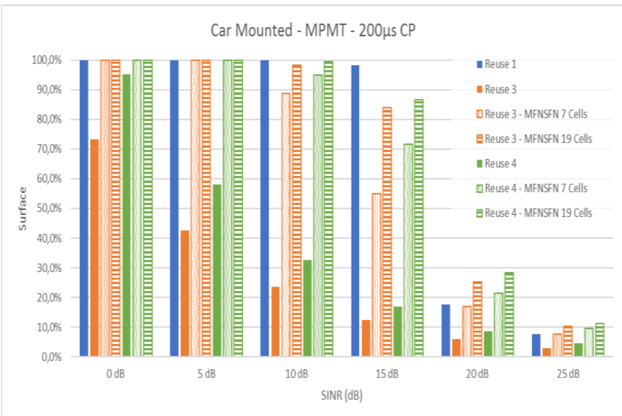


Figure 13 **Figure 14**

Table 2: The main parameters of the homogeneous HPHT and MPMT networks

Layer	ISD (km)	Antenna height a.g.l. (m)	EIRP (in a 5 MHz channel)	Site density (per 10000 km^2 - see note)
HPHT	80	300	79.9 dBm/98 kW	1.8
MPMT	20	80	59.6 dBm/912 W	28.9

Note: Based on the ISD figures in Tables1 & 2.

Observations:

1. The coverage of HPHT and MPMT networks for Car Mounted reception is mainly noise-limited due to low signal levels, this is evident from the low SNR figures obtained in the simulations. However, the coverage of reuse 1 (Single Frequency) Network is significantly better than reuse 3 and 4 (MFNs), due to the constructive contribution of signals inside the CP. The coverage of reuse 3 and 4 networks can be improved with the use of reuse 3 and 4 MFN clusters of SFNs (7 cells in HPHT, 19 cells in MPMT) compared to reuse 3 and 4 "pure" MFNs, due to both the constructive contribution of signals inside the CP and the reduction in co channel interference with the increased co channel separation distance.

2. Compared to a CP of 200 µs, increasing the CP to 300 µs improves, to some extent, the Car Mounted coverage of HPHT and of MPMT reuse 1 as it allows more signals to be constructive and fewer signals to be interfering; but the main limitation for the coverage remains the lack of signal level. Similarly, there is a small improvement in the coverage of reuse 3 and 4 MFN clusters of SFNs. As expected, increasing the CP does not have an impact on reuse 3 and 4 coverages, which correspond to "pure" MFNs.

   The coverage improvement with a CP of 300 µs should be considered mindful of the limitation that it would impose on the speed of movement of the receivers (see § 1.7.2 on Doppler performance). The use of 200 µs for the CP, on the other hand, allows for reception at normal vehicle speeds.

3. An HPHT network alone would offer 10 dB SINR (in 5 MHz) for Car Mounted reception in 87.1% to 96.1% of the target coverage area with 200 µs CP, and slightly more (90.6% to 100%) with 300 µs CP. For 15 dB SINR and higher, the improvement in coverage with 300 µs CP is more significant.

4. An MPMT network alone would offer 15 dB SINR (in 5 MHz) in 86.6% to 98.1% of the target coverage area with 200 µs CP, and slightly more (86.8% to 100%) with 300 µs CP. For 20 dB SINR and higher, the improvement in coverage with 300 µs CP is more significant.

In summary, used individually, homogeneous HPHT and MPMT network types have limitations in terms of coverage and available SINR for Car Mounted reception.

The use of hybrid HPHT+MPMT networks is therefore now evaluated.

Use of Hybrid network (HPHT+MPMT) to further improve the coverage and effect of increasing the EIRP

Figures 15 & 16 show the percentage of surface covered for different target SINR values for Car Mounted reception using a hybrid HPHT+MPMT network having the main characteristics shown in Table 3 (see illustration of Hybrid networks in § 1.2).

A CP of 200 µs was adopted for these hybrid networks, to favour high speed mobile reception. In addition, the effect of increased EIRP was tested by increasing the MPMT EIRP by 7 dB (indicated with “Revised Situation” in Figure 16 compared to the “Base Situation” of Figure 15 where no increase of the MPMT EIRP is considered). This EIRP adjustment would be needed to overcome the self-interference effect in the case the Hybrid network in SFN mode.

To better visualise the improvement achieved from the use of a Hybrid Network, Figures 17 & 18 show a comparison of HPHT layer alone, MPMT layer without the HPHT, MPMT alone (full) and Hybrid HPHT+MPMT. Both Figures 17 & 18 consider a 7 dB increase in EIRP for the full MPMT Network and for the MPMT component of the Hybrid Network.

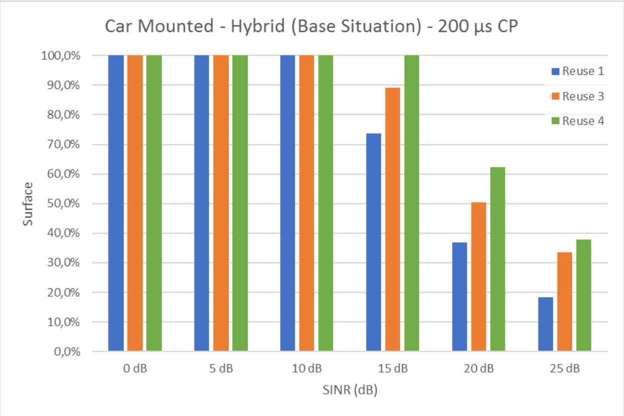


Figure 15

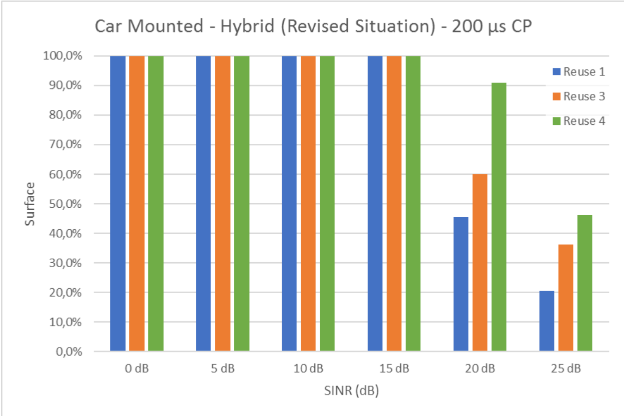


Figure 16

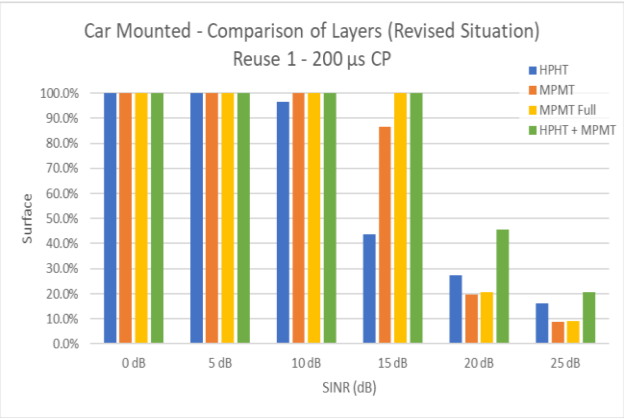


Figure 17

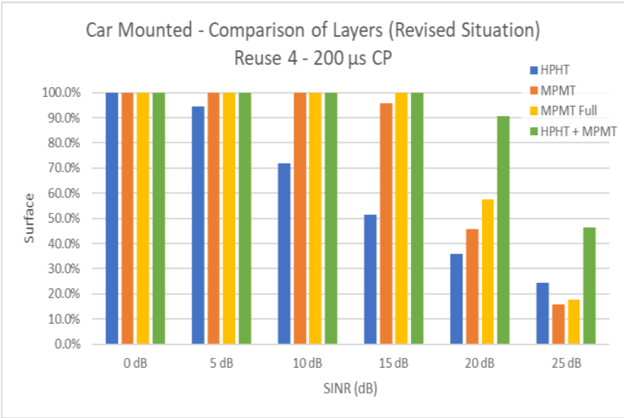


Figure 18

Table 3: The main parameters of the Hybrid Network

Layer	ISD (km)	Antenna height a.g.l. (m)	EIRP (in a 5 MHz channel)	Site density (per 10000 km^2 - see note)
HPHT	80	300	79.9 dBm/98 kW	1.8
MPMT Base situation	23.1	80	59.6 dBm/912 W	21.6

MPMT Revised situation	23.1	80	66.6 dBm/4.6 kW	21.6

Note: Based on the ISD figures in Tables 1 & 3.

Observations:

1. Compared to homogeneous networks in Figures 12 & 14 (reuse 1 pure SFN or reuse 3 or 4 pure MFNs), the hybrid HPHT+MPMT networks in Figure 15 offer a significant increase in coverage for the higher SINR figures (15 dB and above). The improvement shown in Figure 16 is even more significant with the 7 dB increase of EIRP of the MPMT layer transmitters.

2. The increase of the EIRP of the MPMT layer offers a large improvement in the coverage, even with the MPMT layer alone. Figures 17 & 18 indicate that a full MPMT layer (using revised characteristics from Table 3) matches the overall coverage of the Hybrid network for a SINR up to 15 dB. However, for a SINR above 15 dB, the hybrid network exceeds the coverage of any individual homogeneous layer. In particular, a hybrid network with reuse 4 could achieve 20 dB SINR in 90% of the target area.

In summary, a hybrid HPHT+MPMT or a full MPMT 5G Broadcast network with the characteristics shown in Table 3 (MPMT Revised situation) can offer a SINR of 15 dB (in 5 MHz) to Car Mounted receivers in 100% of the target coverage area. This network can be operated either as a general basis or as a solution with reuse 3 or 4 close to the national or regional border areas. The density of sites in such a network is around 21.6 sites per 10000 km^2 (1.8 HPHT + 19.8 MPMT sites per 10000 km^2).

Use of LPLT homogeneous network for Car Mounted reception

Figures 19 & 20 show the percentage of surface covered for different target SINR values for Car Mounted reception using LPLT in Suburban and Urban areas, respectively. The main characteristics of these homogeneous networks are shown in Table 4.

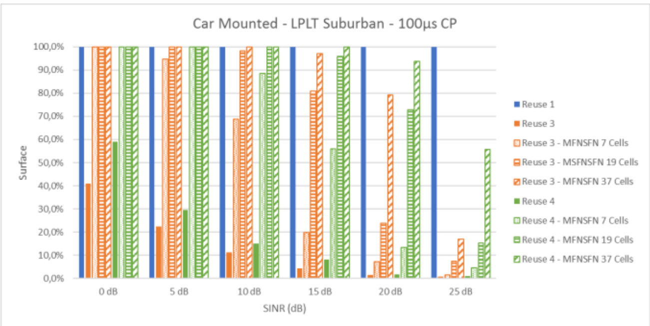


Figure 19

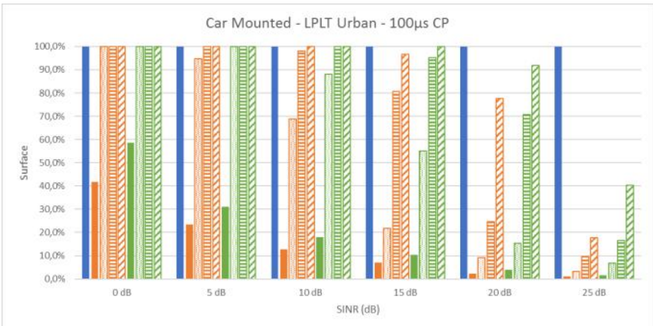


Figure 20

Table 4: The main parameters for the homogeneous LPLT networks

Layer	ISD (km)	Antenna height a.g.l. (m)	EIRP (in a 5 MHz channel)	Site density (per 10000 km^2 - see note)
LPLT	3	30	57 dBm/500 W	1283

Note: Based on the ISD figures in Tables 1 & 4.

Observations:

A CP of 100 µs is suitable for LPLT. Reuse 1 offers the best coverage, ensuring 25 dB SINR in 100% of the target coverage area for Car Mounted reception for both urban and suburban environments.

For the coverage close to national or regional borders, reuse 3 and 4 with MFN clusters of SFNs (19 or 37 cells) can also offer quite high coverage figures: with reuse 4 MFN clusters of SFNs in urban areas, an area coverage of 92% can be achieved for a 20 dB target SINR.

In summary, an LPLT 5G Broadcast network with the main characteristics shown in Table 4 can offer an SINR of 15 dB (in 5 MHz) to Car Mounted receivers in 100% of the target coverage area or 20 dB in 92% of the area for both suburban and urban environments. This network can be operated with reuse 1 inside the national territory, if possible, and with reuse 3 or 4 close to the national or regional border areas, using MFN clusters of SFNs with 37 cells or more.

1.6.2 Networks assessment for Handheld Portable Outdoor reception

Effect of the Cyclic Prefix and the frequency reuse on the coverage

Figures 21 & 22 show the percentage of surface covered for different target SINR values for Handheld Portable Outdoor reception using HPHT with 300 µs CP and 200 µs CP respectively. Figures 23 & 24 show the same type of results but using MPMT. The main characteristics of these homogeneous networks are shown in Table 2, above.

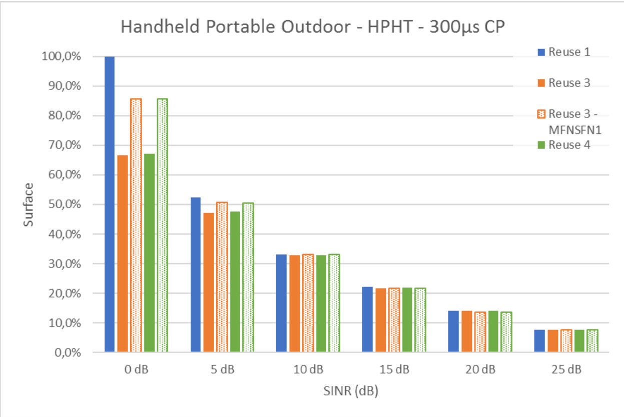


Figure 21

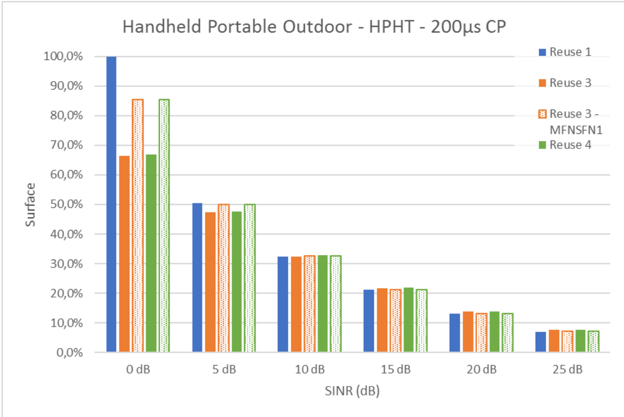


Figure 22

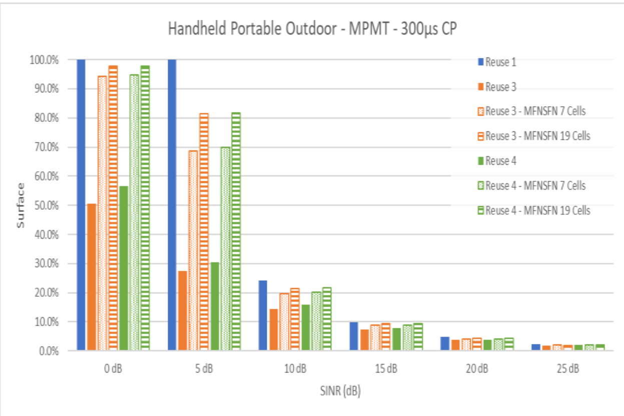


Figure 23

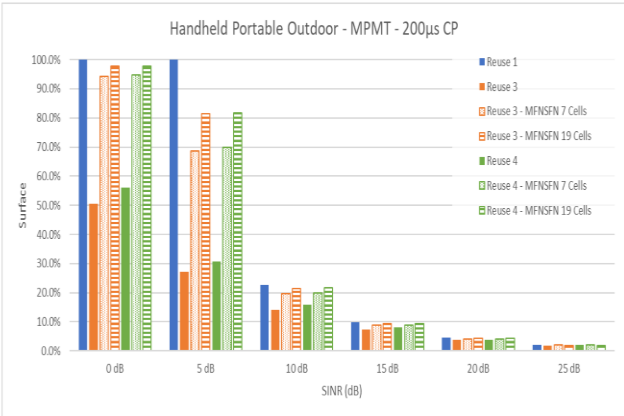


Figure 24

Observations:

1. Figures 21 & 22 show that the coverage of HPHT networks for portable outdoor reception are severely limited by noise due to low signal levels, this is evident from the low SNR figures obtained in the simulations and is due to the high signal margins required for portable reception with handheld receivers. This explains the absence of effect of increasing the CP from 200 µs (Figure 22) to 300 µs (Figure 21).

2. Figures 23 & 24 show that, for reuse 1, the coverage of MPMT networks is better than that of HPHT but is still quite limited in terms of achievable SINR figures. As in the case of Car-Mounted reception (Figures 13 & 14, above), the coverage can be significantly improved with the use of reuse 3 and MFN clusters of SFNs (7 cells in HPHT, 19 cells in MPMT), compared to reuse 3 and 4 “pure” MFNs, due to the constructive contribution of signals inside the Cyclic Prefix and the reduction in co-channel interference with the increased co-channel distance.

In summary, used individually, HPHT and MPMT network types have limitations in terms of coverage and available SINR for Handheld Portable Outdoor reception.

The use of hybrid HPHT+MPMT networks is therefore now evaluated.

Use of Hybrid network (HPHT+MPMT) to further improve the coverage and effect of increasing the EIRP

Figures 25 & 26 show the percentage of surface covered for different target SINR values for Handheld Portable Outdoor reception using a hybrid HPHT+MPMT network having the main characteristics shown in Table 3, above (see illustration of Hybrid networks in § 1.2). A CP of 200 µs was adopted for these hybrid networks for consistency with the simulations for Car-Mounted reception. In addition, the effect of increased EIRP was tested by increasing the MPMT EIRP by 7 dB (indicated "Revised Situation" in Figure 25, compared to the "Base Situation" of Figure 26, where no increase of the MPMT EIRP is considered).

As above, to better visualise the improvement achieved from the use of a Hybrid Network, Figures 27 & 28 show a comparison of HPHT layer alone, MPMT layer without the HPHT, MPMT alone (full) and Hybrid HPHT+MPMT. Both Figures 27 & 28 consider a 7 dB increase in EIRP for the full MPMT Network and for the MPMT component of the Hybrid Network.

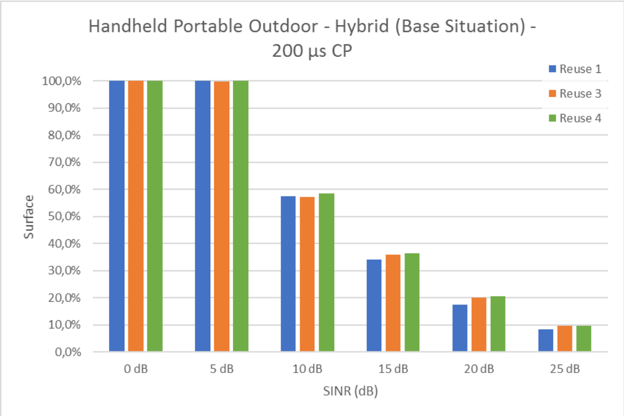


Figure 25

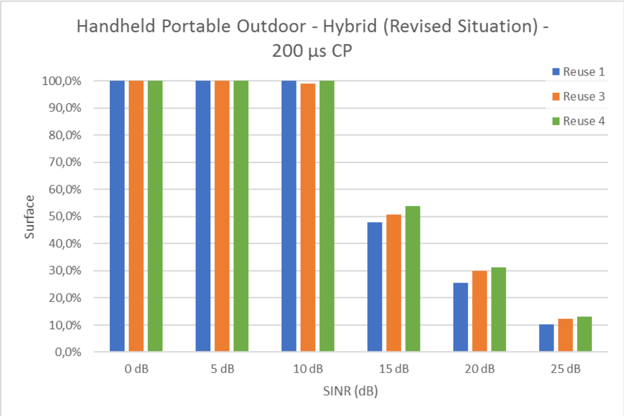


Figure 26

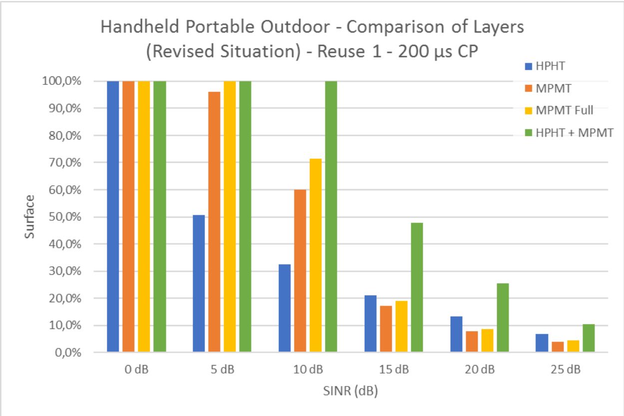


Figure 27

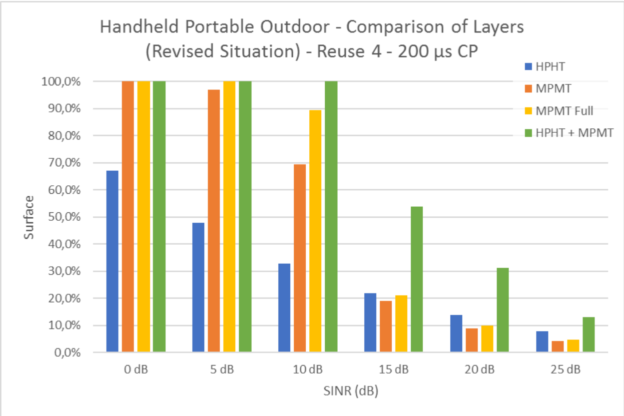


Figure 28

Observations:

The Hybrid networks offer significantly improved coverage for Handheld Portable Outdoor reception compared to the homogeneous networks. In addition, increasing the EIRP of the MPMT layer by 7 dB (from 59.6 to 66.6 dBm) allows for a full area coverage with 10 dB SINR or around 50% coverage with 15 dB SINR.

In summary, a hybrid HPHT+MPMT 5G Broadcast network with the characteristics shown in Table 3 (MPMT Revised situation) can offer a SINR of 10 dB (in 5 MHz) to Handheld Portable Outdoor receivers in 100% of the target coverage area or 15 dB (in 5 MHz) in around 50% of the target coverage area. This network can be operated either as a general basis or as a solution with reuse 4 close to the national or regional border areas. The density of sites in such a network is around 21.6 sites per 10000 km² (1.8 HPHT + 19.8 MPMT sites per 10000 km²).

Use of LPLT homogeneous network for Handheld Portable Outdoor reception

Figures 29 & 30 show the percentage of surface covered for different target SINR values for Handheld Portable Outdoor reception using LPLT in Suburban and Urban areas, respectively. The main characteristics of these homogeneous networks are shown in Table 4. The detailed results are shown in Annex C.

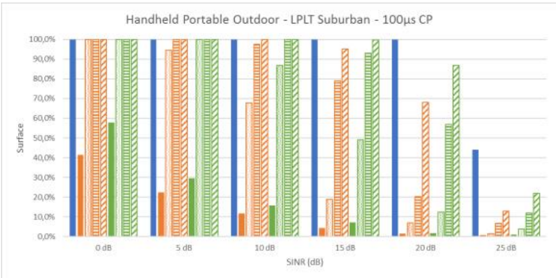


Figure 29

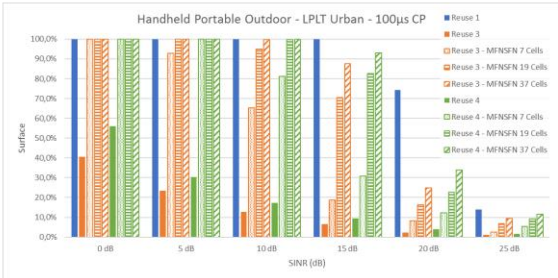


Figure 30

Observations:

A CP of 100 µs is suitable for LPLT. Reuse 1 offers the best coverage, ensuring 20 dB in 100% of the target coverage area in suburban or 15 dB in urban area for Handheld Portable Outdoor reception. For the coverage close to national or regional borders, reuse 3 and 4 MFN clusters of SFNs (19 or 37 cells) can also offer quite high coverage figures: with reuse 4 MFN clusters of SFNs in urban areas, area coverage of 92% can be achieved for a 15 dB target SINR.

In summary, an LPLT 5G Broadcast network with the main characteristics shown in Table 4 can offer a SINR of 15 dB (in 5 MHz) to Handheld Portable Outdoor receivers in 100% of the target coverage area in suburban environment and 92% to 100% in urban environment. This network can be operated with reuse 1 inside the national territory, if appropriate, and with reuse 4 close to the national or regional border areas, using MFN clusters of SFNs with 37 cells.

1.6.3 Networks assessment for Handheld In Car reception

Use of LPLT homogeneous network for Handheld In Car reception

Figures 31 & 32 show the percentage of surface covered for different target SINR values for Handheld In Car reception using LPLT in Suburban and Urban areas, respectively. The main characteristics of these homogeneous networks are shown in Table 4.

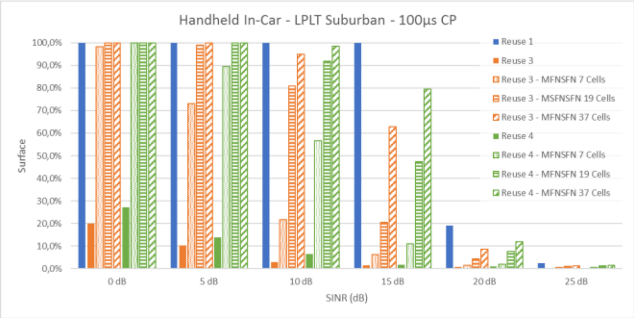


Figure 31

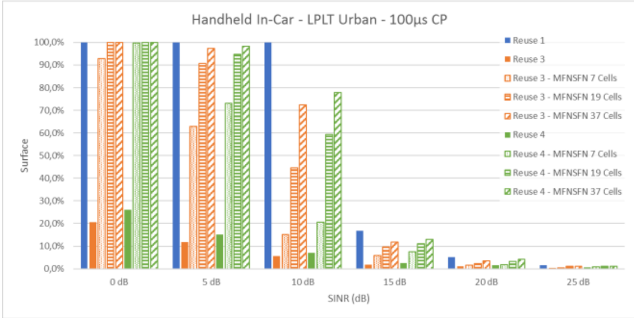


Figure 32

Observations:

The additional margin required for Handheld In Car reception compared with Car Mounted reception imposes further difficulties to insure a sufficient area coverage. For this reason, only the LPLT network type has been evaluated.

Similar to the use of LPLT network for Car Mounted reception, a CP of 100 µs is suitable. Reuse 1 offers the best coverage, ensuring 15 dB in 100% of the target coverage area for Handheld In Car reception for suburban environment and 10 dB in 100% of the target coverage area for urban environment. Reuse 4 with MFN clusters of SFNs (37 cells) can offer quite high coverage figures, reaching 98.5% area coverage for SINR of 10 dB in suburban areas. This coverage is however limited to 77.8% for SINR of 10 dB in urban areas.

In summary, an LPLT 5G Broadcast network with the main characteristics shown in Table 4 can offer a SINR of 10 dB (in 5 MHz) to Handheld In Car receivers in 98.5% to 100% of the target coverage area in a suburban environment and 77.8% to 100% in an urban environment. This network can be operated with reuse 1 inside the national territory, if appropriate, and with reuse 4 close to the national or regional border areas, using MFN clusters of SFNs with 37 cells.

1.6.4 Networks assessment for Fixed Rooftop reception

Effect of the frequency reuse on the coverage

Figures 33 & 34 show the percentage of surface covered for different target SINR values for Fixed Rooftop reception using HPHT and MPMT network, respectively. Only a CP of 300 µs was used in this assessment. The main characteristics of these homogeneous networks are shown in Table 2.

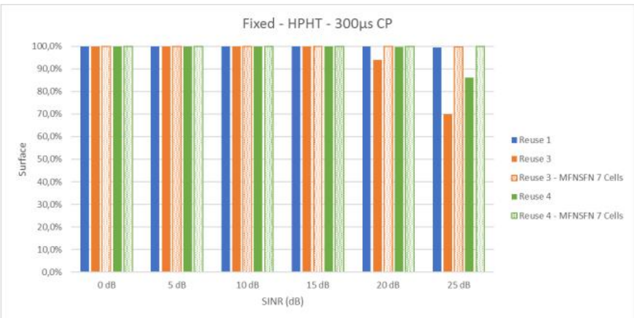


Figure 33

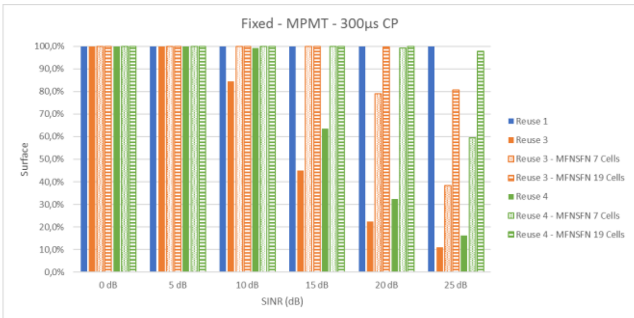


Figure 34

Observations:

Figures 33 & 34 show that HPHT and MPMT networks can offer up to 25 dB SINR with a near full area coverage for Fixed Rooftop reception either with reuse 1 or with reuse 4 MFN clusters of SFNs (7 cells in HPHT, 19 cells in MPMT). The area coverage rate exceeds 99.5% with HPHT and 97.8% with MPMT.

In summary, an HPHT or an MPMT 5G Broadcast network with the main characteristics shown in Table 2 can offer an SINR of 25 dB (in 5 MHz) to Fixed Roof Top receivers in 99.5% and 97.8% of the target coverage area, respectively. This network can be operated with reuse 1 inside the national territory, if appropriate, and with reuse 3 for HPHT or 4 for MPMT close to the national or regional border areas, using MFN clusters of SFNs with 7 cells for HPHT and 19 cells for MPMT. Reuse 4 MFN clusters of SFNs offers an equivalent area coverage to reuse 1 full SFN.

1.7 Specific analysis

1.7.1 Impact of practical antenna pattern

The generic studies to assess 5G Broadcast coverage are based on idealised, omnidirectional antenna patterns, where networks use HPHT and MPMT infrastructure and an optimized tri-sector pattern for LPLT sites. However, the real-world implementation of 5G Broadcast could be based both on existing antennas and on new antennas, where it is possible and cost-effective to install such new antennas. For the range of site topologies considered in this report (LPLT, MPMT and HPHT) the currently implemented antennas have been designed to meet existing network requirements and direct use by 5G Broadcast may lead to sub-optimum performance.

For sites that are currently in use for conventional Broadcasting, a single antenna array comprising several individual radiating elements provides uniform azimuthal coverage over the required arc; often a full 360 degrees. In reality, and due to constraints in practical antenna design, a ripple of up to 4 dB is the best that can generally be achieved, and the existing broadcast sites may be considered to be optimised for conventional broadcasting and also for 5G Broadcast.

For sites that are currently used by the Mobile Network, the situation is rather different. Generally, the antennas are constructed from arrays of elements providing 120 degree 'sector' azimuthal coverage. Where coverage is required over a full 360 degrees, three such antennas are mounted at 120-degree intervals around the structure. Where specific geographical areas are targeted, sector antennas may be oriented accordingly. The existing unicast mobile network can select and energise these sector antennas independently and so any interaction between adjacent sectors is not important – the base station scheduler may ensure that adjacent antennas are not used on the same resource block at the same time. However, if this arrangement of sector antennas is simultaneously powered from a single transmitter, as may be the case for 5G Broadcast applications, the interaction between adjacent antennas should be considered as this may lead to a compromise in the overall performance [13].

The sector antennas typically used by mobile systems are not designed to operate as arrays. If so used for 5G Broadcast, such arrays would have deep nulls in the radiated pattern, which may compromise coverage. Measures to mitigate this loss in coverage may be required. Existing broadcast antenna systems have already been optimised for coverage. See Annex E for more information.

The impact on coverage could be reduced by increasing the EIRP, adopting an increased phase delay between sector antennas (cyclic delay diversity), a combination of the two or building a new antenna with a better pattern. Each has a cost implication that needs to be weighed against the potential loss in coverage. Again, see Annex E for more information.

1.7.2 Estimate of Doppler performance

For a 5G Broadcast system targeting mobile reception, system Doppler performance is important as, via the carrier spacing and hence the choice of Cyclic Prefix (CP), it can drive the network design.

Doppler is an issue for broadcast systems. DAB systems largely avoid the problem because of the low frequency employed, around 200 MHz. DTT systems are typically designed for Fixed reception where Doppler is generally not a problem. DTT systems designed for portable/mobile reception (as, for example, in Germany) employ increased carrier spacing (fewer carriers i.e., larger frequency spacing between carriers) and hence smaller SFN size along with more dense networks (reduced spacing between transmitters).

The ISD in an SFN is dependent on the length of the CP. The larger the ISD, the longer the CP needs to be, and correspondingly a longer symbol time is needed. However, longer symbol time, which is a function of the inverse of the carrier spacing, will result in degraded Doppler performance and lower speed limits for mobile reception.

Without doing detailed and complicated link-level simulations, the calculation of Doppler performance for OFDM-based broadcast systems can be estimated from methods described in [16], which investigate the Inter Carrier Interference (ICI, or FFT leakage) as a function of Doppler. This work focused on DVB-T/T2 but the methodology is applicable to any OFDM system, including 5G Broadcast.

The report of this work contains an extensive mathematical analysis but ends up with a “simple” formula for an OFDM system with 1 kHz carrier spacing:

$$C/I = 58.6 - 20\ log_{10}\,(f_d) \quad \text{dB}$$

Where: f_d is the Doppler frequency in a Rayleigh fading channel in Hertz.

For example, 100 Hz Doppler results in a "C/I" = 58.6 - 40 = 18.6 dB. If the required C/N of the system is known, it is easy to calculate the C/N degradation. Usually, a 3 dB increase of required C/N is used when presenting the Doppler frequency limits and corresponding speed limits. The maximum theoretical Doppler may also be calculated.

Modifications:

- **Changing the FFT (symbol time)** will change the constant 58.6 in the equation. For example, 500 Hz carrier spacing (16k FFT) will reduce the value by 6 dB, and for 250 Hz carrier spacing (32k FFT) by 12 dB, resulting in constant values of 52.6 dB and 46.6 dB, respectively.
- **Other symbol times** may be scaled correspondingly; for example, a factor 2 corresponds to 6 dB, means that, for example, a factor of 1.8 should be 4 (6 dB in linear scale) x 1.8/2.0. Converted back to dB scale the correction to 58.6 would be 5.6 dB.

ICI is, however, not the only limitation. Additionally, the limitations created by the channel estimation, CE, (determined by the Pilot Patterns) need to be determined. These Scattered Pilot Patterns are used for channel estimation in the receiver, in frequency and in time[12]. But in the case of 5G Broadcast the FFT leakage (ICI) seems to be the main limitation, at least for the OFDM variants of interest in SFNs.

In the tables below the maximum Doppler and speed limitation for 5G Broadcast are derived for three proposed 5G Broadcast modes operating at 600 MHz.

[12] The repetition pattern in frequency is denoted Dx or Df, while the repetition pattern in time is denoted Dt or Dy

Table 5: Maximum Doppler Frequency & Speed
Symbol time 400 µs, Cyclic Prefix 100 µs, Df(Dx) 2, Dt(Dy) 1 (see footnote 12)
Channel estimation max Doppler 1250 Hz

Req C/N [dB] - Rayleigh	Channel Estimation Doppler Max [Hz]	FFT Leakage Fd Max	Max Doppler [Hz]	Max Speed [km/h]
0	1250.0	1202.3	1202.3	2164
5	1250.0	676.1	676.1	1217
10	1250.0	380.2	380.2	684
15	1250.0	213.8	213.8	385
20	1250.0	120.2	120.2	216
25	1250.0	67.6	67.6	122

Table 6: Maximum Doppler Frequency & Speed
Symbol time 800 µs, Cyclic Prefix 200 µs, Df(Dx) 3, Dt(Dy) 2 (see footnote 12)
Channel estimation max Doppler 625 Hz

Req C/N [dB] - Rayleigh	Channel Estimation Doppler Max [Hz]	FFT Leakage Fd Max	Max Doppler [Hz]	Max Speed [km/h]
0	625	602.6	602.6	1085
5	625	338.8	338.8	610
10	625	190.5	190.5	343
15	625	107.2	107.2	193
20	625	60.3	60.3	108
25	625	33.9	33.9	61

Table 7: Maximum Doppler Frequency & Speed
Symbol time 2700 µs, Cyclic Prefix 300 µs, Df(Dx) 3, Dt(Dy) 1 (see footnote 12)
Channel estimation max Doppler 185.2 Hz

Req C/N [dB] -Rayleigh	Channel Estimation Doppler Max [Hz]	FFT Leakage Fd Max	Max Doppler [Hz]	Max Speed [km/h]
0	185.2	186.2	185.2	333
5	185.2	104.7	104.7	188
10	185.2	58.9	58.9	106
15	185.2	33.1	33.1	60
20	185.2	18.6	18.6	34
25	185.2	10.5	10.5	19

In conclusion, a Cyclic Prefix of 200 µs seems to be required to ensure mobile reception with reasonable maximum speed.

1.8 Capacity versus SINR

Tables D1, D2 and D3 in Annex D provide an indicative mapping of the 5G Broadcast system capacity with the corresponding signal to noise and Interference ratio (SINR) in various reception environments, for a 5 MHz channel. They are based on the recent results relative to link level simulations of different 5G Broadcast configurations presented in [14] for various SINR values. The link level simulations presented in [14] do not cover all configuration cases and all reception modes. Moreover, for Fixed reception, they correspond to the use of one antenna, while for portable / mobile reception two antennas are assumed, leading to diversity gain in the receivers. As such they provide an upper bound on the capacity associated with a given SINR value.

Based on the information of Annex D, Tables 8 to 10 give an indicative mapping of the key SINR values reflected in § 1.6 with the corresponding capacity (upper bound) for the different CP values and target reception modes.

Table 8: Upper bound on capacity for 100 μs CP and key SINR values

SINR (dB)	Car Mounted Handheld In car Capacity (Mbit/s) in a 5 MHz channel	Handheld Portable Outdoor Portable Indoor Handheld Portable Indoor Capacity (Mbit/s) in a 5 MHz channel	Fixed Rooftop Capacity (Mbit/s) in a 5 MHz channel
0	-	-	N/A
5	2.161	2.161	N/A
10	4.282	4.844	N/A
15	7.543	7.792	N/A
20	10.413	11.162	N/A
25	12.262	13.198	N/A

Table 9: Upper bound on capacity for 200 μs CP and key SINR values

SINR (dB)	Car Mounted Handheld In car Capacity (Mbit/s)	Handheld Portable Outdoor Portable Indoor Handheld Portable Indoor Capacity (Mbit/s)	Fixed Rooftop Capacity (Mbit/s)
0	-	-	-
5	2.161	2.535	2.535
10	4.282	4.844	4.844
15	7.043	7.792	7.792
20	8.915	11.162	11.162
25	(> 9.664)	(>12.262)	(>12.262)

Table 10: Upper bound on capacity for 300 µs CP and key SINR values

SINR (dB)	Car Mounted Handheld In car Capacity (Mbit/s)	Handheld Portable Outdoor Portable Indoor Handheld Portable Indoor Capacity (Mbit/s)	Fixed Rooftop Capacity (Mbit/s)
0	-	-	-
5	-	3.097	3.097
10	-	6.201	6.201
15	-	10.304	10.304
20	-	15.239	13.770
25	-	(>15.239)	(>15.239)

1.9 Conclusions from simulation results on theoretical Networks

It should be possible to ensure 15 dB SINR in 5 MHz for 5G Broadcast Car Mounted receivers with full rural area coverage using a Hybrid HPHT+MPMT network with HPHT EIRP similar to current typical DTT HPHT networks and with MPMT EIRP slightly higher than current typical DTT MPMT networks.

Reuse 1 should be used where possible and reuse 3 or 4 MFN clusters of SFNs should be used where reuse 1 cannot be implemented, typically at regional and national borders. A CP of 200 µs is recommended to allow reception at normal vehicle speeds. In these conditions, in a 5 MHz channel, a capacity up to 7.043 Mbit/s could be achieved (1.4 b/s/Hz).

A full LPLT network could provide 15 dB SINR in 5 MHz for 5G Broadcast Car Mounted receivers with full urban and suburban area coverage. Considering the large site density for this type of network (1283 sites per 10000 km^2), its use may be limited to the coverage of urban and suburban areas with reuse 1, with rural areas being more efficiently covered by Hybrid HPHT+MPMT networks as described above, with a site density around 21.6 sites per 10000 km^2. The same capacity as above, i.e., up to 7.043 Mbit/s, could be achieved.

5G Broadcast Handheld In Car reception with 15 dB SINR is not achievable across a full area for any of the analysed network types. The coverage for this type of reception would be limited to best effort.

The same Hybrid HPHT+MPMT described above would also ensure 15 dB SINR in 5 MHz for Handheld Portable Outdoor reception in 50% of rural areas. It should be noted that the coverage in terms of population in rural areas could be higher than the area coverage if the choice of the sites is made adequately.

A complementary reuse 1 LPLT network, as described above, is necessary in suburban and urban areas to ensure 15 dB SINR for Handheld Portable Outdoor in these areas. In these conditions and using the same MCS as for Car Mounted, a capacity up to 7.043 Mbit/s could be achieved. Otherwise, if a dedicated network for Handheld Portable Outdoor reception is selected, a capacity up to 7.792 Mbit/s could be achieved.

Fixed Rooftop reception of 5G Broadcast with 15 dB SINR in 5 MHz should be possible from the networks described above, at least with the same coverage areas as for Car Mounted and Handheld Portable receptions. However, if rooftop reception is primarily targeted, HPHT or MPMT networks currently used for DTT could ensure 25 dB in 5 MHz for 5G Broadcast Fixed Rooftop reception with near full area coverage.

Near full population coverage would also be expected with these networks. Reuse 1 could be used when possible and reuse 3 or 4 MFN clusters of SFNs could be used when reuse 1 cannot be implemented, especially at regional and national borders. A 300 µs CP may be required, which is not suitable for mobile reception. In these conditions, a dedicated network would be needed for this reception mode.

The available information on link level simulations does not allow assessment of what capacity could be achieved. It is only possible to say that this capacity will exceed 15.239 Mbit/s in 5 MHz.

2. Real Networks

One of the key drivers for broadcasters' and broadcast network providers' interest in adopting 5G Broadcast is making their content available to handheld devices such as mobile phones and tablets.

A critical question is whether the existing broadcast infrastructure used for DAB or DTT, possibly complemented with cellular type networks, can be used to provide such handheld services using 5G Broadcast. Therefore, simulations have been carried out based on existing real network sites to see if this could be an option and under what conditions this would be feasible.

Two implementations of 5G Broadcast networks based on existing broadcast infrastructure have been modelled. The first network, in Italy, is based upon one developed for the former DVB-H implementation on the existing DVB-T channel 38 national SFN, augmented by mobile operator sites. The second network is based on the national DAB network deployed in Denmark.

2.1 Italy

The coverage of a 5G Broadcast network based on the existing DVB-T channel 38 SFN network[13] augmented by additional mobile network operator sites has been assessed.

2.1.1 5G Broadcast sites

This network, consisting of 821 sites of a BNO (Broadcasting Network Operator), is a real existing national network designed for Fixed reception that provides useful roof top coverage to more than 94% of the population. It consists of a mixture of HPHT, MPMT and LPLT.

To extend coverage for handheld/mobile use, the network was augmented by two sets of existing Mobile Network Operator (MNO) sites. The first set (1037) of MNO sites is a large part of those that were used in one of the two former DVB-H networks in Italy. A second set of (1253) MNO sites is considered to complete the coverage, see Table 11.

Table 11: Sites considered for the 5G Broadcast Network in Italy

Sites	North (reg. 1-10)	South (reg. 11-20)	Italy
BNO	458	363	821
MNO part #1	581	456	1037
MNO part #2	596	657	1253
sum	1635	1476	3111

[13] This BNO network is one of the two former DVB-H Networks and is now operating in DVB-T, 8k, 64-QAM, code 3/4, IG 1/4, SFN mode.

2.1.2 5G Broadcast planning assumptions

For coverage modelling, the BNO sites used existing ERP and the MNO sites used an ERP of 200 W[14] (328 W EIRP). The propagation model used is ITU-R P.1812 for 1% time with coverage step of 100 m. DTM (Digital Terrain Model) and clutter[15] definition is 100 m x 100 m. The CAS was not considered as a constraint.

To optimise coverage, SFN delay "fine tuning" is done in all the sites of the Northern area.

Coverage was calculated for Handheld Portable Outdoor (1.5 m a.g.l.) using the parameters in Table 12, considering different values of C/N and starting with a CP of 200 μs, in line with the 5G Broadcast system parameters Variant 4 (Annex A, Table A1) and with the reception parameters of Scenario 3 for Handheld Portable Outdoor (Annex A, Table A2).

Additional calculation was done also for Car Mounted (CM) using the reception parameters of Scenario 1 for Car Mounted (Annex A, Table A2).

Table 12: Calculation parameters

Scenario	1	3
Reception parameters	Car Mounted (CM)	Handheld Portable Outdoor (HH PO)
Type of reception	Mobile	Portable
Path type	Land/Sea	Land/Sea
Receiver height (m)	1.5	1.5
Bandwidth	5 MHz	5 MHz
Receiver Noise Figure (dB)	6	9
Receiver feeder loss (dB)	0	0
Other losses (dB)	1	1
Frequency	610 MHz (CH 38)	610 MHz (CH 38)
Receiver antenna gain, including body loss and receiver diversity gain (dBi)	3	5.8
Receiver strategy for signals from the same SFN	Maximum C/I	Maximum C/I
Location variation standard deviation (dB)	5.5	5.5

Table 13 shows the values of field strength that are required for different C/N and as a function of the "location probability"[16], using the parameters presented in Table 12.

[14] Licensing requirements in Italy limit the ERP that can be readily deployed.

[15] The propagation model has been tuned (for the current P.1812 model) to the clutter using field measurement data obtained (in years 2007 - 2008) from the DVB-H former network. These "fine-tuning" measurements were limited to the area of the City of Milan and surrounding municipalities, including some rural "flat" areas, but should be considered as valid for the whole Country, also.

[16] Location probability is the percentage of receiving locations inside any "small area" (typically 100m by 100m) of the coverage where a given field strength is achieved or exceeded.

The values of field strength presented in Table 13, together with the DTM and the clutter[17] , were used for the calculation of the coverage at 1.5 m.

Any “small area” that satisfies the requirement on the given location percentage is considered as covered with all its surface and its population. Vice versa, in any “small area” where this requirement is not satisfied, all its surface and all its associated population are considered as not covered.

To obtain the “useful coverage”, one additional “C/(N+I)” calculation is needed (using the appropriate values of C/N and Field strength threshold wanted), to identify the percentage of the coverage that is “lost”, due to the SFN self-interference.

Unless otherwise specified, all the “coverages” specified from here onwards should be understood as “useful coverages”, whereby the percentage of self-interference is already taken into account, subtracting its value from the (gross) coverage.

[17] E.g., in the Urban Environment, the height of the building is assumed as “20 m” and, from the measurement done, 3 dB of additional clutter attenuation was also factored in.

Table 13: Example of calculations of the "minimum median field strength"

Unit	Values	5G Broadcast Handheld portable outdoor (HH PO)				5G Broadcast Car mounted (CM)			
dB	C/N	**5**	**10**	**15**	**20**	**5**	**10**	**15**	**20**
Ws/K	Boltzmann's Constant k	1.38E-23				1.38E-23			
K	Absolute temperature T_0	290				290			
Hz	Equivalent noise bandwidth	5.00E+06				5.00E+06			
dBm	Thermal Noise power	-107.0				-107.0			
dB	Noise figure	9.0				6.0			
dBm	**KTBF**	**-98.0**				**-101.0**			
ohm	Input resistance	75				75			
dB	Other losses	1.0				1.0			
dB	**C/N and other losses**	**6.0**	**11.0**	**16.0**	**21.0**	**6.0**	**11.0**	**16.0**	**21.0**
dBm	**Min. Rx input power**	**-92.0**	**-87.0**	**-82.0**	**-77.0**	**-95.0**	**-90.0**	**-85.0**	**-80.0**
dBµV	Min. equiv. Rx input voltage	16.8	21.8	26.8	31.8	13.8	18.8	23.8	28.8
MHz	Frequency	610				610			
dB	Rx feeder loss	0.0				0.0			
dBi	Rx ant. Gain (incl. diversity) iso	-5.8				3.0			
dBd	Rx antenna gain over a dipole	-7.9				0.9			
dB	Antenna factor (75 Ω)	29.9				21.1			
dB	Height loss	0.0				0.0			
dBµV/m	**(dBu) Min. field strength**	**47**	**52**	**57**	**62**	**35**	**40**	**45**	**50**
dB	Standard deviation σ	5.5				5.5			
	Location probability 70%								
dB	Location correction factor	3				3			
dBµV/m	**Min. median field strength**	**50**	**55**	**60**	**65**	**38**	**43**	**48**	**53**
	Location probability 90%								
dB	Location correction factor	7				7			
dBµV/m	**Min. median field strength**	**54**	**59**	**64**	**69**	**42**	**47**	**52**	**57**

2.1.3 5G Broadcast Coverage Predictions

In this section, results obtained for handheld receivers and PO reception with CP 200 µs, C/N 15 dB and 90% Location Probability are initially presented.

The BNO Broadcast network provides the basic coverage of 59.4% of the population of all Italy. Example coverage of North Italy is provided in Figure 35 (coverage is higher than for South Italy) and the population covered is 68.1%. See Table 14 for additional results.

Table 14: Coverage in the North, South and all of Italy for two combinations of network

HH Po, Loc. 90%, CP 200 µs

Network	C/N dB	Threshold E dBµV/m	Coverage %			Interference %			Useful %		
			North	South	Total	North	South	Total	North	South	Total
BNO	15	64	69.0	50.6	60.4	0.9*	1.1*	1.0*	68.1	49.5	59.4

BNO +MNO #1 and #2	15	64	90.8	82.9	87.1	2.2*	2.2**	2.2**	88.6	80.7	84.9

* Calculated value (delay optimization for all sites)
** hypothesis.

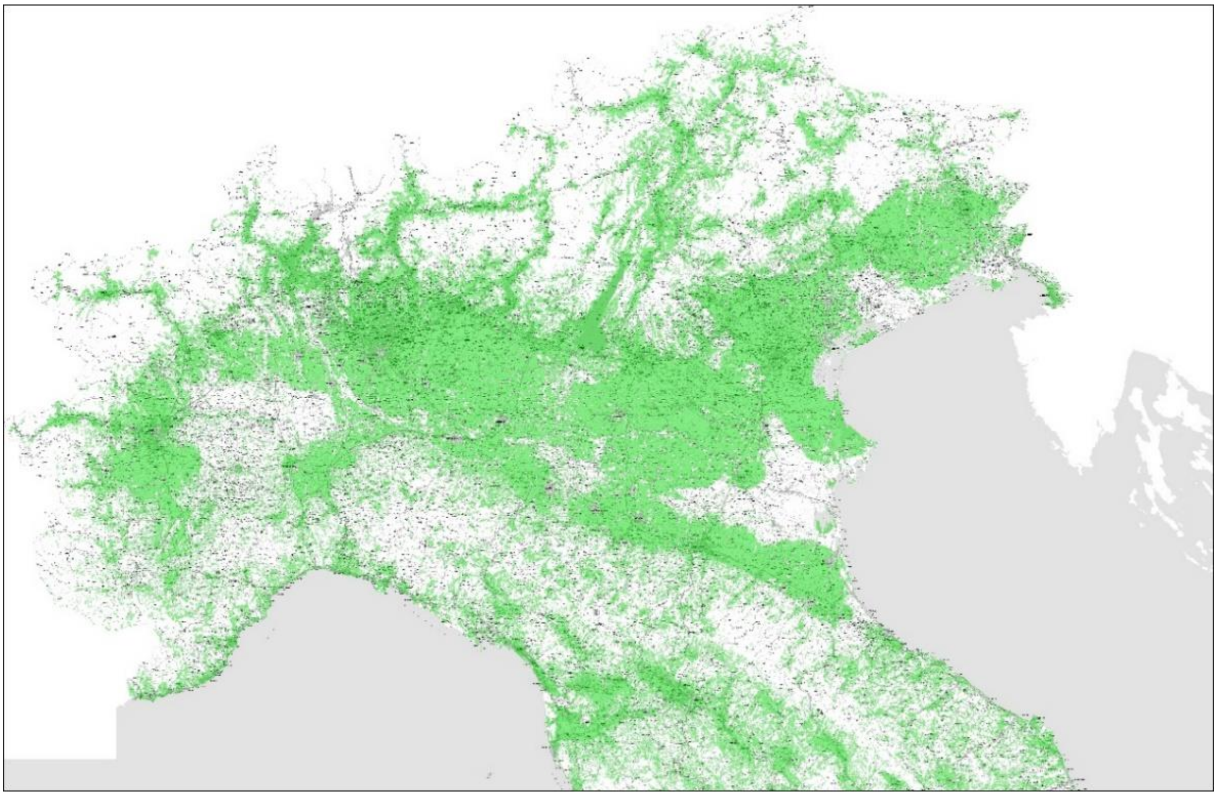


Figure 35: North Italy BNO Useful Coverage, C/N 15 dB

Figures 36 & 37 show the results of the coverage using the MNO part #1 only and with MNO part#1 and part #2 sites, respectively. Therefore, the coverage of the BNO network can be enhanced by the addition of these MNO sites.

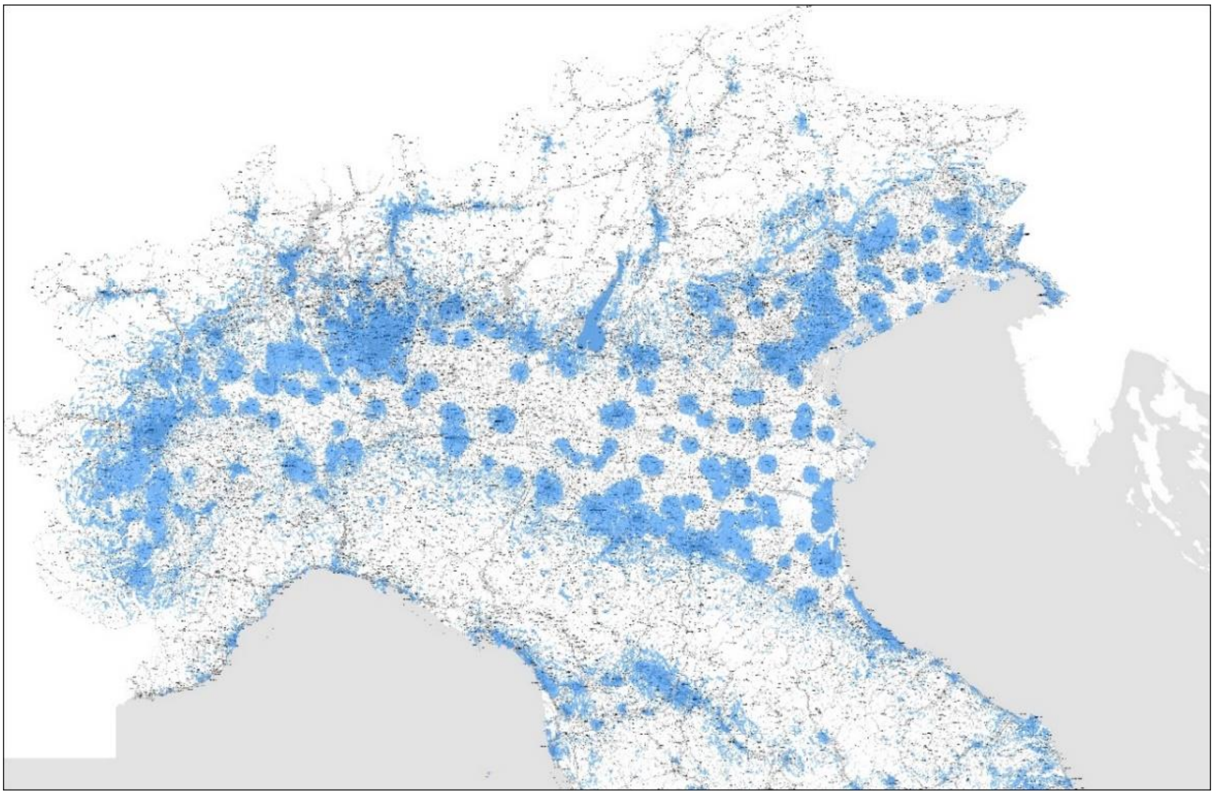


Figure 36: North Italy MNO #1 Useful Coverage, C/N 15 dB

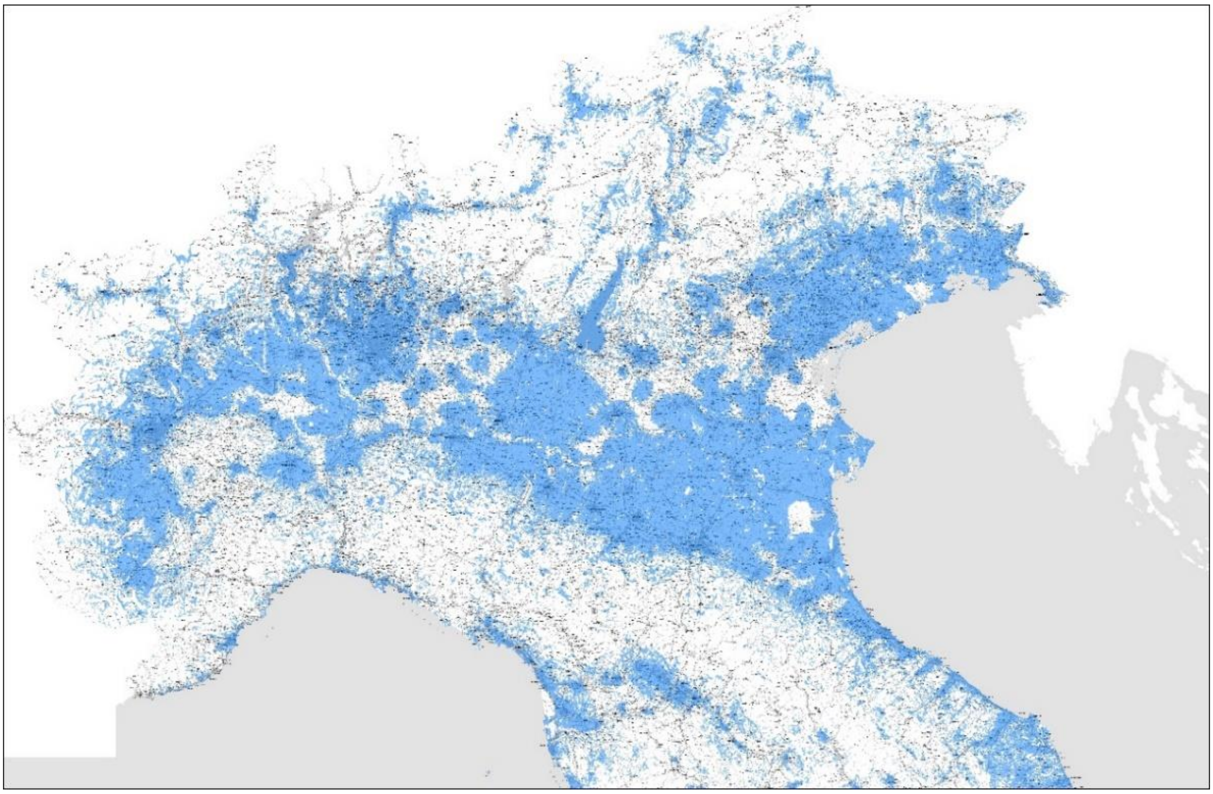


Figure 37: North Italy MNO #1 and #2 Useful Coverage, C/N 15 dB

In the North of Italy, using a combination of the different sites, BNO and MNO part #1 cover 82.0% of the population (Figure 38), while BNO, MNO part #1 and MNO part #2 cover 88.6% (Figure 39).

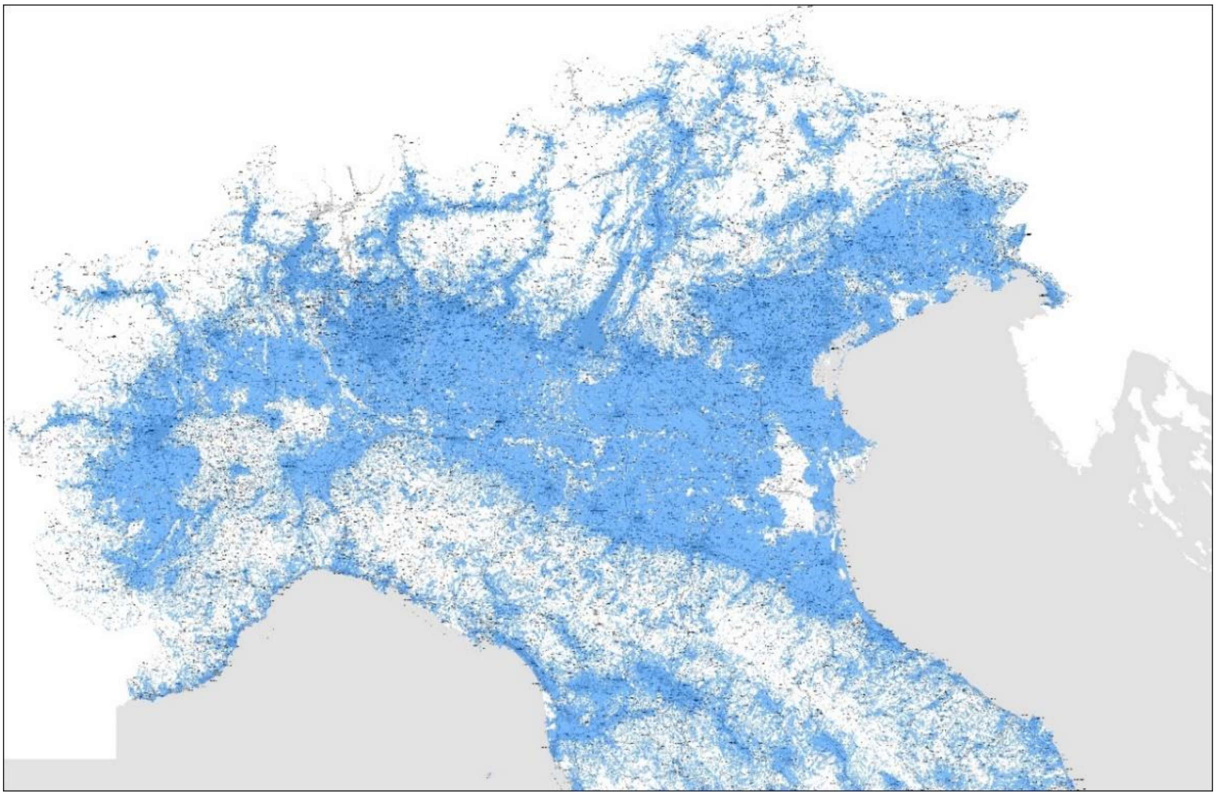


Figure 38: North Italy BNO + MNO#1 Useful Coverage, C/N = 15 dB

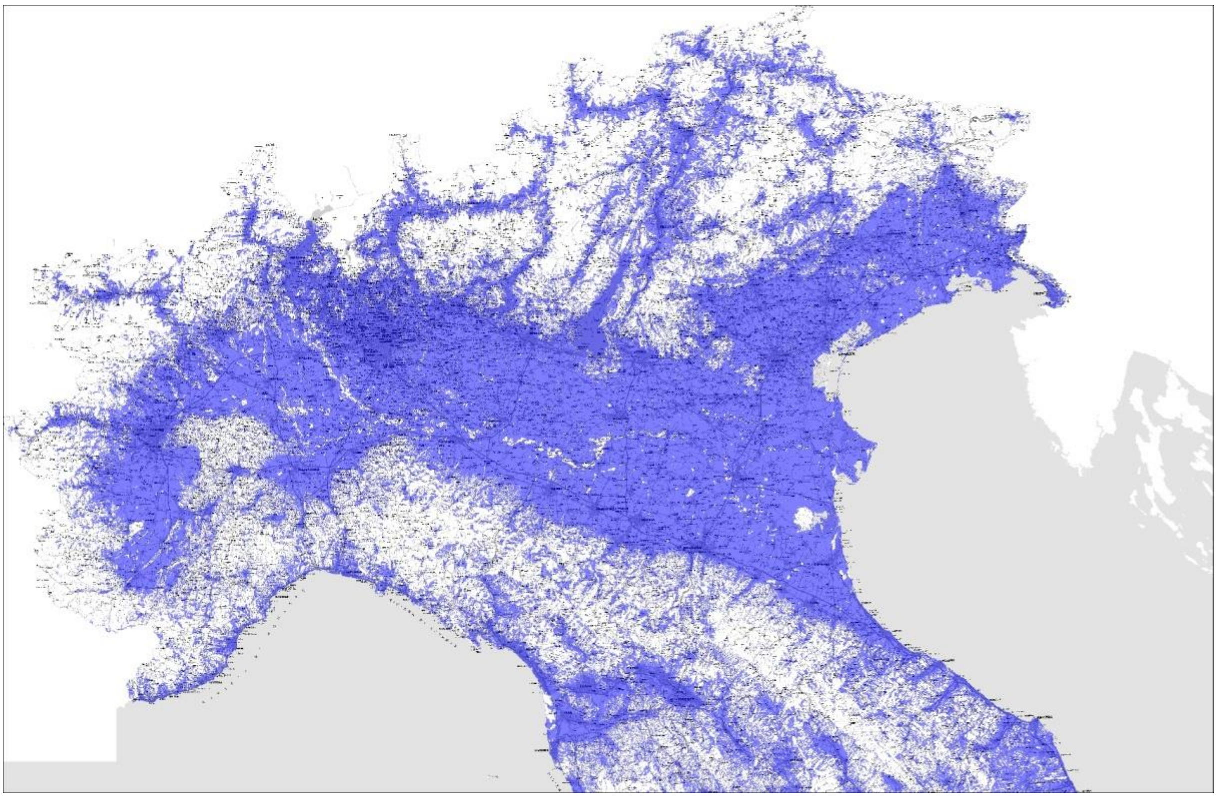


Figure 39: North Italy BNO+MNO#1+MNO#2 Useful Coverage, C/N = 15 dB

Figure 40 shows the same coverage as presented in Figure 39, with the "best server" at a given location between the BNO and the 2 MNO sets of sites.

BNO coverage (green) is 43.6% of the total coverage; MNO#1 (blue) is 32.6%; MNO#2 (yellow) is 12.4%.

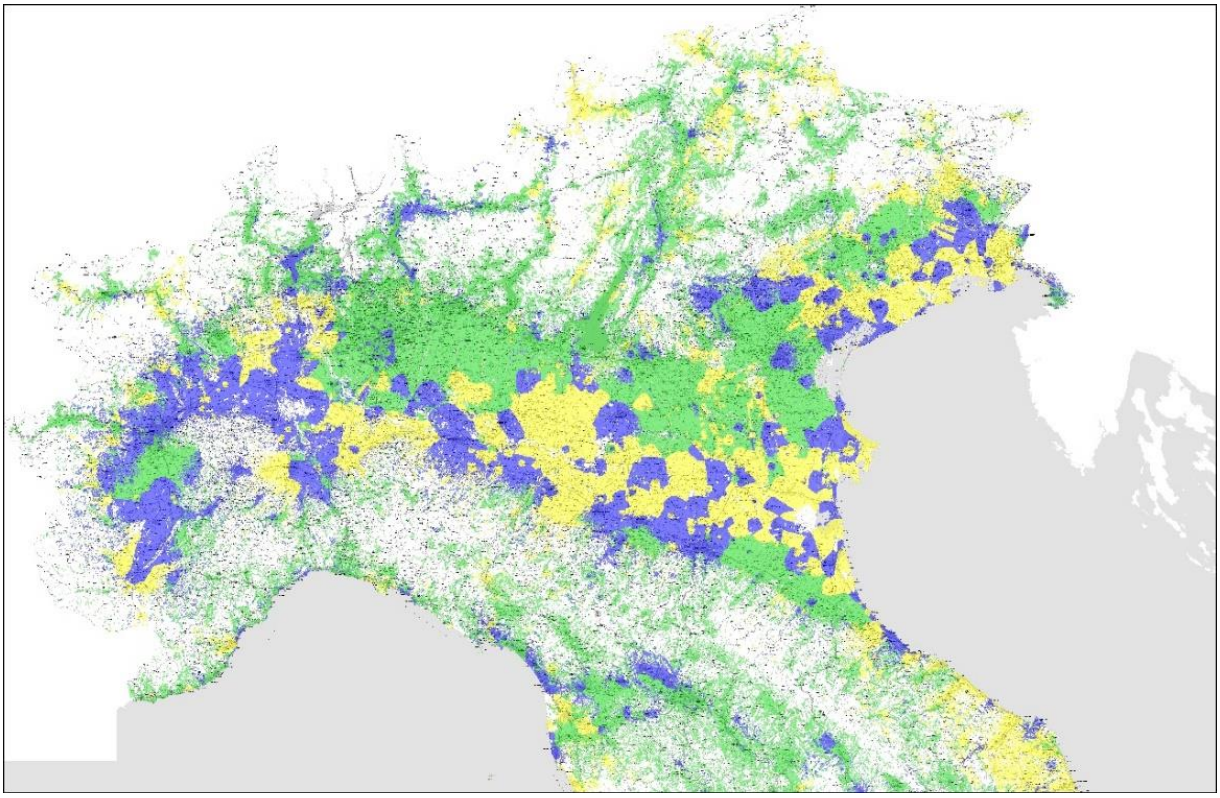


Figure 40: North Italy BNO+MNO#1+MNO#2 “Best Server” Useful Coverage, C/N = 15 dB

Overall useful coverage (in terms of percentage of population) of the network combinations is given in Table 15 (70% location probability), Table 16 (90% location probability) and Table 17 (95% location probability).

The coverage depends on the required location probability over the “small areas” (typically a square with a side of 100 m) that comprise the useful coverage[18].

Table 15: Coverage of the network combinations (location probability 70%)

	North Italy (HH PO) *(reg. 1-10) 200 µs - Loc 70%*			
C/N Sites	5 dB	10 dB	15 dB	20 dB
BNO	94.8	90.6	79.8	63.1
MNO part #1	84.3	78.6	66.5	51.2
MNO part #1 & #2	87.6	83.2	74.9	60.2
BNO + MNO part #1	96.1	94.0	89.0	79.1
BNO + MNO part #1 & #2	**96.7**	**95.0**	**91.4**	**83.0**

[18] E.g., if the requirement is 90% of location probability, any “small area” (or “pixel”) with percentage of locations <90% is considered as “not covered”: therefore, all its surface and the associated population is considered as “not covered”.

If all the percentages are counted (and, e.g., any pixel covered at 50% of its location “contributes” for the 50% of its surface and population to the whole coverage and so on), in case of the network composed by BNO + MNO part #1 and #2, the value 87.4% of useful coverage for C/N = 15 dB becomes 89.0% (see Table 15).

Table 16: Coverage of the network combinations (location probability 90%)

	North Italy (HH PO) *(reg. 1-10) 200 μs - Loc 90%*			
C/N **Sites**	**5 dB**	**10 dB**	**15 dB**	**20 dB**
BNO	92.3	83.5	68.1	49.8
MNO part #1	80.8	71.3	56.1	41.4
MNO part #1 & #2	85.4	79.7	68.5	51.8
BNO + MNO part #1	94.9	91.5	83.9	70.0
BNO + MNO part #1 & #2	**95.8**	**93.7**	**88.6**	**76.3**

Table 17: Coverage of the network combinations (location probability 95%)

	North Italy (HH PO) *(reg. 1-10) 200 μs - Loc 95%*			
C/N **Sites**	**5 dB**	**10 dB**	**15 dB**	**20 dB**
BNO	89.8	78.2	60.9	42.6
MNO part #1	77.9	66.0	50.9	34.6
MNO part #1 & #2	84.0	76.9	63.3	45.6
BNO + MNO part #1	94.0	89.3	79.9	63.7
BNO + MNO part #1 & #2	**95.3**	**92.7**	**85.9**	**70.3**

The relative timing of sites for optimising coverage is important, as shown in Figures 41 & 42.

In case of CP = 200 μs, C/N 15 dB and 90% of location probability, the percentage of usefully covered population increases by the order of 7% (from 81.8% with “zero delay” to 88.6% with “optimised site timing”).

Note that this coverage would be of the order of 90% but, even with all the optimizations done, a percentage of the order of 2.0% - 2.5% for the SFN self-interference remains, reducing the useful coverage.

The positive effect of the “site timing” for the SFN coverage is clearly visible in Northern Italy, in the flat areas between all the major HT HP Broadcasting Sites (e.g., between Turin and Milan, Milan and Verona, Bologna and Venice).

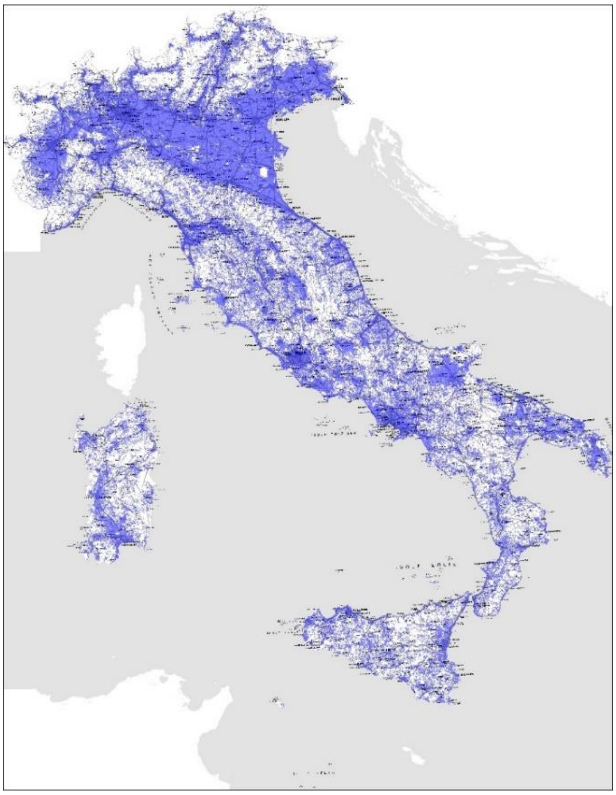


Figure 41: Optimised relative site timing

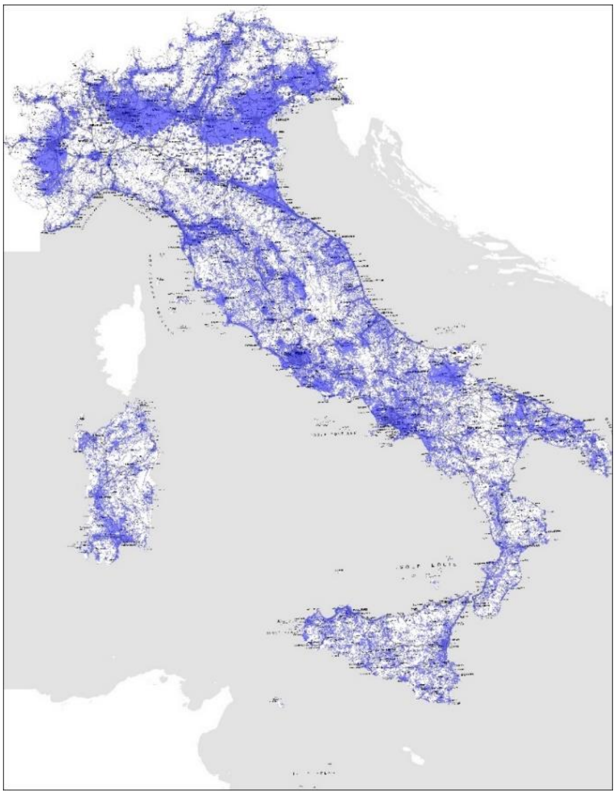


Figure 42: All sites co timed (zero delay)

The impact of extending the cyclic prefix on coverage was also investigated, see Table 18 for the coverage of the population in Northern Italy.

Italic values in the Table are the estimated advantage of adopting a CP of 300 µs rather than 200 µs. This gain is usually[19] greater when the number of sites increases and for higher values of C/N.

[19] When considering only the two sets of MNO sites, the maximum advantage is around C/N = 15 dB, which decreases for greater values of C/N. In this implementation, LPLT sites of MNOs are (relatively) near one to each other and, especially for high values of C/N, their coverage is limited by the received field strength, rather than by the effect of the SFN auto-interference "outside the CP".

Table 18: Coverage for two different CP values (% of population)

	North Italy (HH PO) *(reg. 1-10) 200 µs - Loc 90%*				North Italy (HH PO) *(reg. 1-10) 300 µs - Loc 90%*			
C/N Sites	5 dB	10 dB	15 dB	20 dB	5 dB	10 dB	15 dB	20 dB
BNO	92.3	83.5	68.1	49.8	*92.4* *0.1*	*83.7* *0.2*	*68.4* *0.3*	*50.1* *0.3*
MNO part #1	80.8	71.3	56.1	41.4	*80.9* *0.1*	*71.8* *0.5*	*56.7* *0.6*	*42.1* *0.7*
MNO part #1 & #2	85.4	79.7	68.5	51.8	*85.7* *0.3*	*81.0* *1.3*	*70.5* *2.0*	*53.6* *1.8*
BNO + MNO part #1	94.9	91.5	83.9	70.0	*95.0* *0.1*	*91.9* *0.4*	*84.9* *1.0*	*71.5* *1.5*
BNO + MNO part #1 & #2	95.8	93.7	88.6	76.3	*95.9* *0.1*	*94.3* *0.6*	*90.3* *1.7*	*79.1* *2.8*

Finally, the coverage of Car Mounted is considered. Table 19 shows the results of the useful coverage for CM 95% locations, 200 µs and different network combination. Values in *italics* are the estimated percentage of SFN auto interference.

Note that the useful coverage CM for 95% locations is very similar to the useful coverage CM for 99% locations and the HH PO for 50% of locations.

Table 19: Coverage for Car Mounted receiving condition (% of population)

	North Italy (Car mounted) *(reg. 1-10) 200 µs - Loc 95%*				North Italy (Handheld PO) *(reg. 1-10) 200 µs - Loc 95%*			
C/N Sites	5 dB	10 dB	15 dB	20 dB	5 dB	10 dB	15 dB	20 dB
BNO	95.6 *0.5*	92.5 *1.0*	84.5 *2.3*	69.2 *3.2*	89.8 *0.5*	78.2 *0.6*	60.9 *0.7*	42.6 *0.6*
MNO part #1	85.5 *0.4*	80.8 *1.5*	70.5 *4.4*	55.9 *5.4*	77.9 *0.7*	66.0 *1.3*	50.9 *1.4*	34.6 *2.9*
MNO part #1 & #2	88.5 *0.6*	84.3 *2.3*	76.7 *6.0*	63.0 *11.5*	84.0 *0.5*	76.9 *1.8*	63.3 *2.7*	45.6 *2.5*
BNO + MNO part #1	96.5 *0.2*	94.8 *0.7*	90.4 *2.5*	81.3 *5.8*	94.0 *0.2*	89.3 *0.6*	79.9 *1.3*	63.7 *2.0*
BNO + MNO part #1 & #2	**97.1** *0.2*	**95.5** *0.7*	**92.2** *2.6*	**84.7** *7.2*	**95.3** *0.2*	**92.7** *0.6*	**85.9** *2.0*	**70.3** *3.4*

For the network composed by BNO + MNO part #1 and #2 sites, Figure 43 shows a graph of the results as a function of some possible receiving conditions and for different C/N values. Moreover, additional results for CM and HH PO can be obtained with a simple interpolation of other available data.

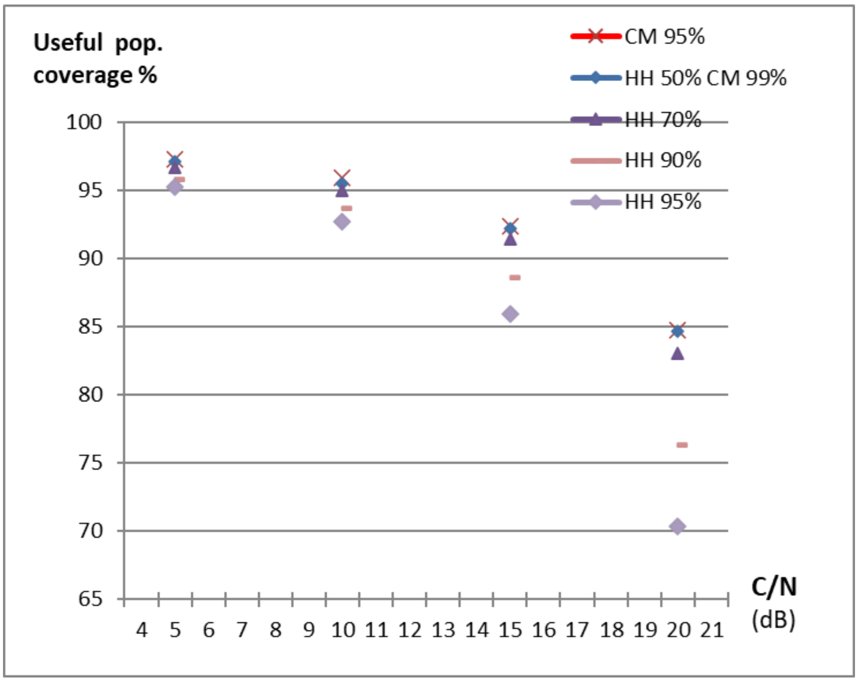


Figure 43: Coverage for CM and HH for different location probability and C/N values (BNO + MNO part #1 + MNO part #2)

2.1.4 Conclusions

The coverage of BNO and MNO sites of this SFN (reuse 1) network is considered satisfactory with a CP of 200 µs. BNO coverage is important to reduce the overall number of sites that are needed. The MNO sites are important to cover with continuity inside urban zones. The SFN static delay of all the sites always needs to be optimized ("fine tuning" of the sites and of their relative "static delays" is mandatory).

The "complete" network composed of BNO and MNO sites, can give a useful coverage greater than 92% of population with 15 dB C/N (location probability 95%) for Car Mounted reception.

For Handheld Portable Outdoor, this network can give a useful coverage around 93% of population with 10 dB of C/N (location probability 95%) or around 86% of population with 15 dB of C/N (location probability 95%).

The results are dependent on the requirement for the location statistical distribution over any of the specified "small areas" (or "pixel of coverage"), typically a square with a side of 100 m that comprise the coverage. Adopting a too large percentage of "location probability" for a given receiving condition may lead to an underestimate of its actual coverage, especially for C/N values of the order of 15 dB or greater.

Extending the CP from 200 µs to 300 µs helps to synchronize the SFN sites but will compromise the performance in case of mobile reception.

2.2 Denmark

This case study considers the coverage of a 5G Broadcast network based on the existing Broadcast infrastructure in Denmark, evaluating whether such a network can provide Car Mounted (mobile) or Handheld Indoor/Outdoor reception using LTE-based 5G Broadcast according to 3GPP Release 16, FeMBMS. The *PROGIRA® plan* broadcast network planning software was used in the study.

2.2.1 Danish Radio Broadcast infrastructure

The broadcast sites used are the existing T-DAB and DVB-T2 sites used by Danish Radio. The T-DAB sites are part of 3 different VHF SFNs, providing near universal mobile and indoor coverage. The DTT sites are mainly used to provide rooftop reception at UHF. For the 5G Broadcast simulations the site characteristics were modified slightly. The real antenna heights were used but the ERPs were modified as shown in Table 20:

Table 20: Antenna heights and ERPs

Antenna height [m]	ERP [kW]	Number of transmitters
190 - 290	50	12
100 - 190	10	16
50 - 100	5	22
<50	2	8

Number of stations:	58
Transmitter spacing:	30 - 50 km
ERP:	2 – 50 kW
Frequencies:	UHF channel 37 (602 MHz)
Antenna height:	30 – 290 m
Polarisation:	Vertical

In summary, the network can be considered as something in between a HPHT and a MPMT network. The 5G Broadcast network is simulated as a national SFN. No antenna or timing optimisation were made to reduce potential SFN self-interference. Figure 44 shows the locations of the sites.

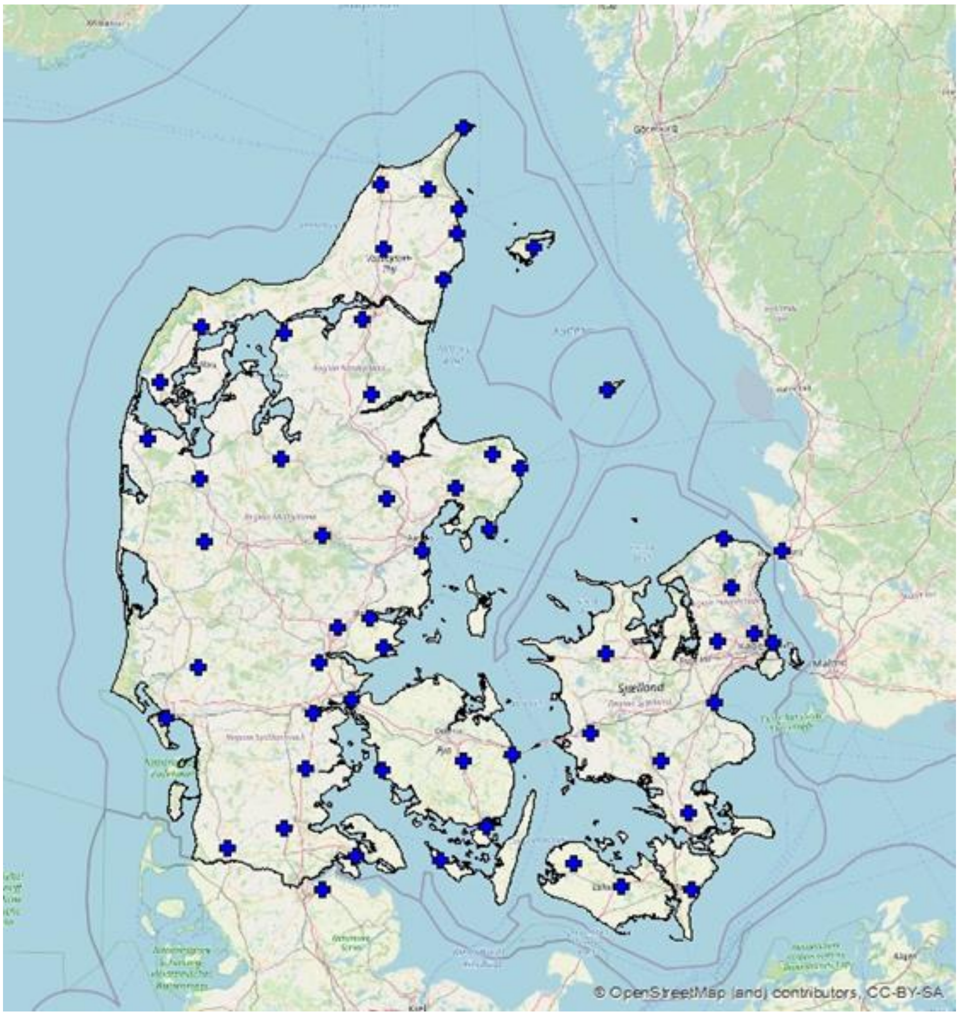


Figure 44: The Danish DAB sites used in the study (58 sites in total)

2.2.2 5G transmission modes and planning parameters

Several different 5G transmission modes were simulated. They represented a range from very robust modes using QPSK, requiring low C/(N+I) values and providing little capacity, to modes using 256-QAM, requiring high C/(N+I) values and providing capacity equivalent to DVB-T2 transmissions used today. As there is currently some uncertainty regarding the capacity achieved for a certain C/N for 5G Broadcast, the results are presented as population covered for available C/(N+I), from 0 to 25 dB in steps of 5 dB, i.e., for 0, 5, 10, 15 ,20 and 25 dB. It is, however, easy to translate the results to capacity when consolidated mappings from C/N to capacity are available for the different reception cases.

The CP has been set to 200 µs and 300 µs to evaluate the influence of using different CP values.

The bandwidth (BW) of the 5G Broadcast signal is set to 5 MHz, to align with the Monte Carlo simulations in the previous sections.

The planning parameters agree with § A1 (Annex A), i.e., the same parameters as in the Monte Carlo simulations are used. Some of these parameters are presented below. The reception scenarios that are considered in the study are highlighted in Table 21. These are Car Mounted mobile reception, Handheld Portable Outdoor reception and Handheld Portable Indoor reception.

Table 21: Planning parameters used in the coverage simulations

Scenarios	Car mounted (CM)	Handheld In Car	Handheld portable outdoor	Fixed rooftop	Portable indoor	Handheld portable indoor
Type of reception	Mobile	Mobile	HH Portable	Fixed	Portable	HH Portable
Receiver antenna gain, (dBi)	3	8.3	8.3	13	4.3	8.3
Receiver diversity gain	0	2.5	2.5	0	6	2.5
Entry loss (dB) - Building/vehicle	0	9	0	0	11	11
Standard deviation of Building Entry loss (dB)	0	5	0	0	6	6
Receiver height (m)	1.5	1.5	1.5	10	1.5	1.5
Receiver feeder loss (dB)	0	0	0	4	0	0
Other losses (dB)	1	1	1	1	1	1
Receiver Noise Figure (dB)	6	9	9	6	9	9
Required Location Percentage	95%	95%	95%	95%	95%	95%

When assessing coverage, the possible impact of the CAS (Cell Acquisition Subframe) in 5G Broadcast was not considered. To allow the receiver to correctly interpret the Broadcast content, the CAS in 5G Broadcast needs to be received and decoded. The CAS should in theory be very robust, but there is currently some uncertainty regarding how well the CAS will perform in real cases.

2.2.3 Planning software and databases

To assess coverage the PROGIRA® software[20] was used. 5G Broadcast coverage was simulated using a dedicated 5G Broadcast module. The field strength predictions were made using the CRC Predict terrain-based propagation model. The propagation model was tuned to the clutter and height data in Denmark using field measurement data. Mean error is near 0 dB with a spread (standard deviation) between 5 and 7 dB around UHF 600 MHz. The following geographical databases were used:

- Terrain Elevation data (25 m).
- Clutter data (50 m), which includes 5 different classes representing built areas (dense urban, urban, suburban, residential, and industrial).
- Population data (100 m).

The wanted field strength has been calculated using 50% of time propagation and the interfering field strength with 1.7% of time (to assess potential SFN self-interference).

[20] https://www.progira.com/spectrum-planning-software/

2.2.4 Results for 200 µs Cyclic Prefix

To start with the C/(N+I) (SINR) for the network was calculated.

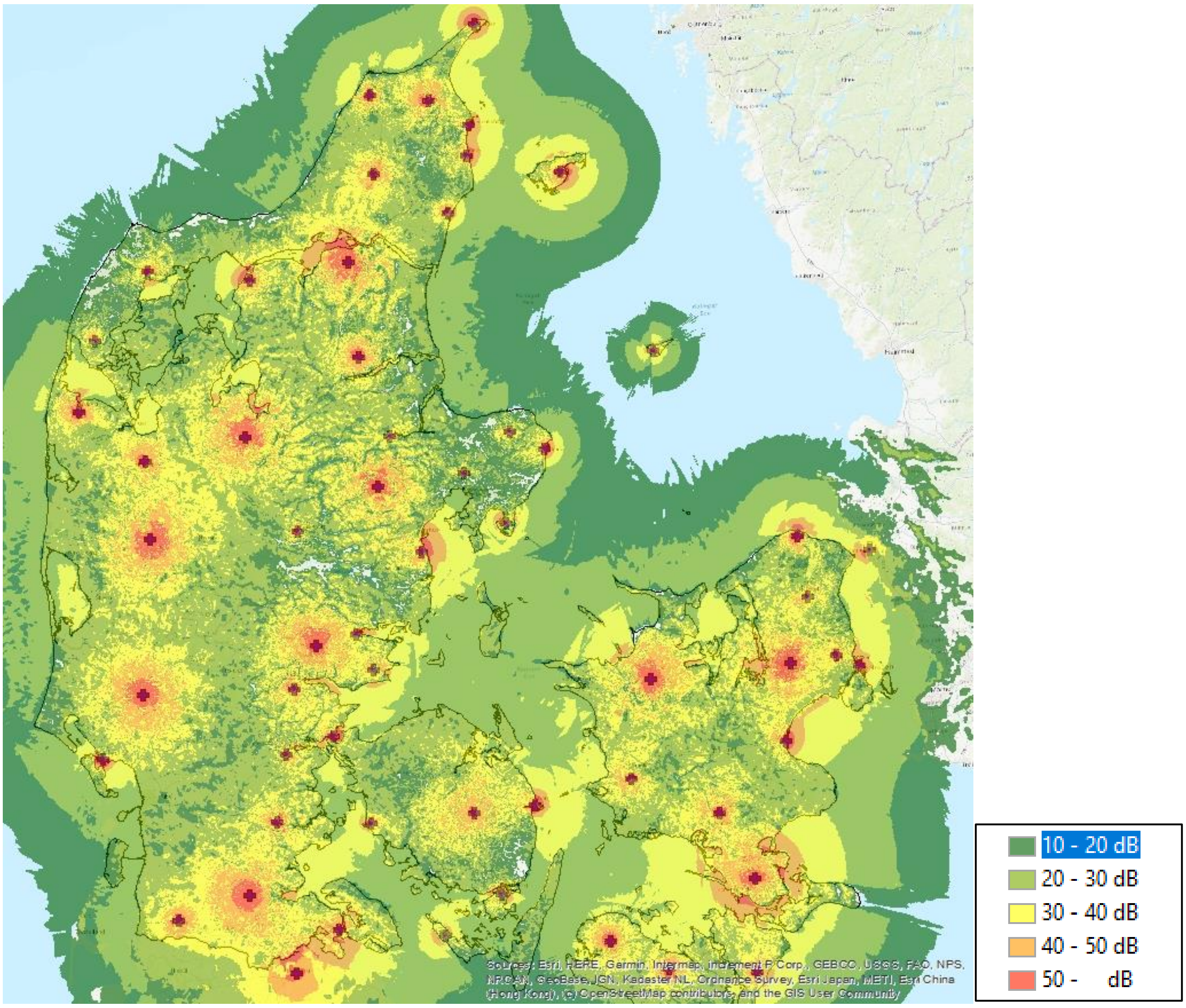


Figure 45: Median (50% of locations) Raw achievable C(N+I) mobile

From the map in Figure 45, it seems that it is possible to achieve a C/(N+I) above 20 dB in a large part of the country. It should however be kept in mind that this is the median C/(N+I), valid for 50% of locations. For broadcast services we normally use a target service probability of 95% of locations or even 99% for mobile reception. Additionally, we need to be able to evaluate the impact of possible SFN self-interference in the network, which may occur if the Cyclic Prefix is not long enough. This is particularly important for the less robust modulation and code rate (MCS) in 5G Broadcast, where SFN self-interference can be substantial.

SFN simulations for the different required C/(N+I) are presented in Table 22 (CP 200 µs).

Table 22: Population coverage for 95% of locations for CP of 200 µs

C/N Req [dB] Mobile Car Mounted	Population (No SFN self-interference) [% of total pop] 95% locations	Population (With SFN self-interference) [% of total pop] 95% locations
0	99.2	92.4
5	98.9	82.7
10	97.7	64.9
15	94.1	42.1
20	86.5	22.1
25	82.6	10.2

Table 22 shows that the coverage, when not considering SFN self-interference, is quite good. The network can provide coverage to 94% of population at 15 dB C/N+I. But when SFN self-interference is considered, the coverage drops significantly. Figure 46 illustrates the difference in surface coverage between two C/N+I thresholds, taking SFN self-interference into consideration

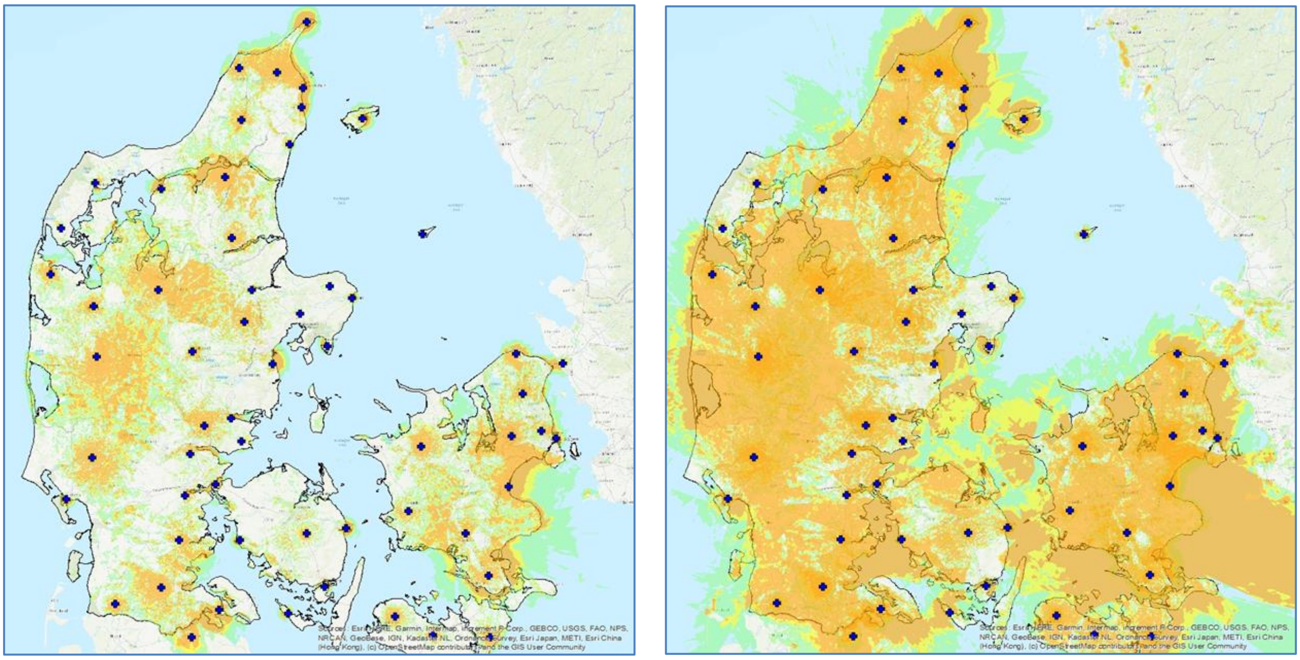


Figure 46: Mobile Car mounted coverage, C/(N+I) of 20 dB (left) and 10 dB (right) at 95% of locations for CP of 200 µs.

The main limitation at higher required C/N values is SFN self-interference. From this the conclusion to be drawn is that it might be difficult to use a MCS which requires a higher C/N than, say, 5 dB, resulting in very limited capacity for mobile Car Mounted reception. It should, however, be borne in mind that the case of a national SFN in Denmark is a critical case. The country is very flat and there are sea paths between the different Islands, which results in high field strengths for 1.7% of time. In the example no further attempts to optimize transmitter timing and antenna directions to reduce SFN self-Interference were made. Such an optimisation would of course improve coverage, but due to the large impact it would not be realistic to implement such a large SFN using a CP of 200 µs.

Summarizing the results for all three reception cases for 200 µs CP are Table 23 and Figure 47.

Table 23: population coverage for Car mounted, Handheld Indoor and Handheld Outdoor reception using a CP of 200 µs

C/N	Handheld Indoor %	Car Mounted %	Handheld Outdoor %
0 dB	82.7	92.4	92.5
5 dB	71.5	82.7	82.7
10 dB	47.5	64.9	64.9
15 dB	22.7	42.1	41.6
20 dB	7.8	22.1	21.3
25 dB	2.6	10.2	9.3

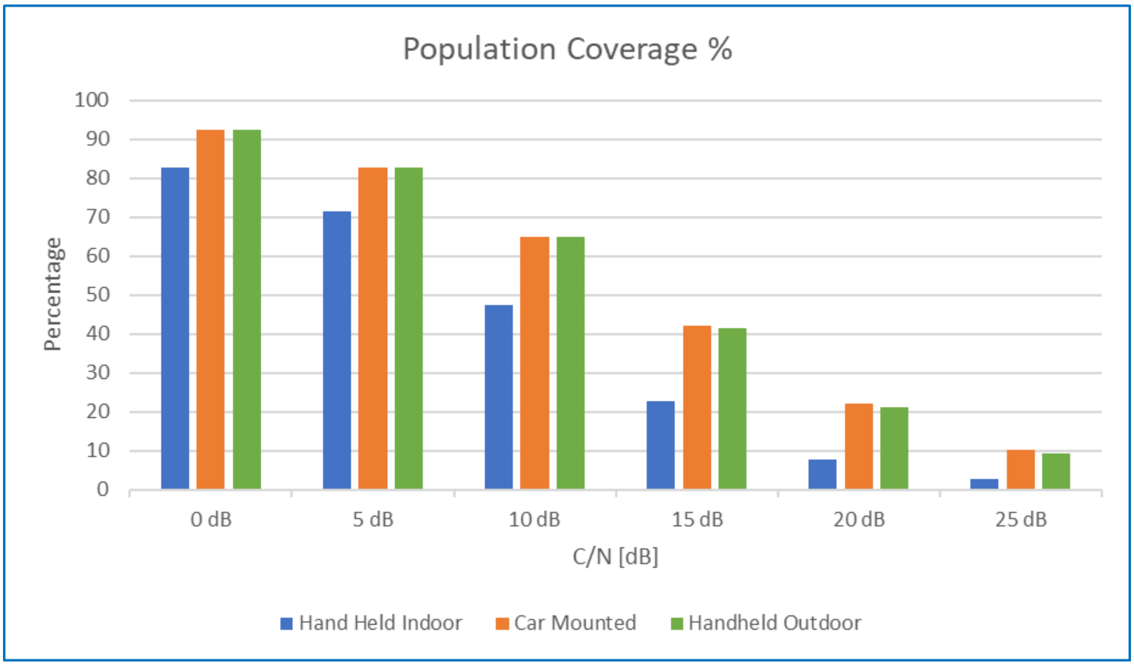


Figure 47: Graphical results for CP of 200 µs

We can conclude that for Handheld Indoor reception, coverage is mainly limited by lack of field strength. For Car Mounted and Handheld Outdoor coverage it is limited mainly by SFN self-interference, in particular at higher required C/(N+I). Moreover, a CP of 200 µs is not long enough to work in larger SFNs using high power broadcast sites.

2.2.5 Results for a cyclic prefix of 300 µs

If we do the calculation using a CP of 300 µs. We will see a significant improvement in SFN coverage. In the case of Mobile Car Mounted reception we get the results shown in Table 24.

Table 24: Population coverage for 95% of locations for CP of 300 µs.

C/N Req [dB] Mobile Car Mounted	Population (No SFN self-interference) [% of total pop] 95% locations	Population (With SFN self-interference) [% of total pop] 95% locations
0	99.3	99.3
5	99.3	99.3
10	99.3	99.3
15	99.3	99.2
20	99.1	98.3
25	98.2	92.9

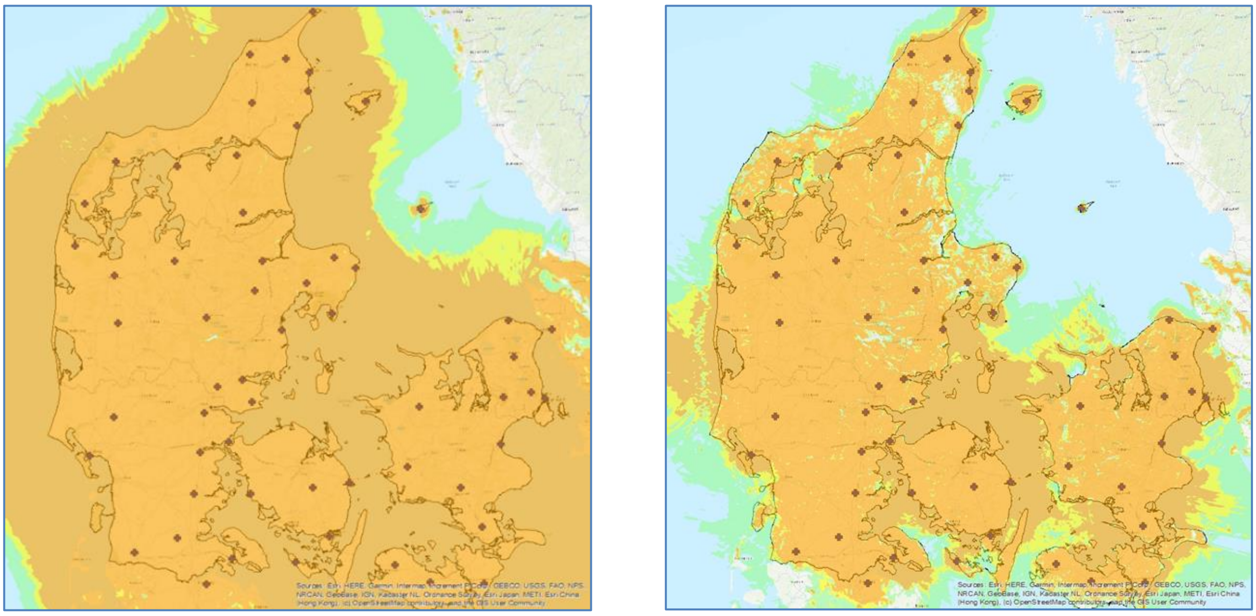


Figure 48: Mobile Car mounted coverage, C/(N+I) of 15 dB (left) and 25 dB (right) at 95% of locations for CP of 300 µs.

The "only" difficulty with using a CP of 300 µs is the sensitivity to Doppler. According to § 1.7.2, limitation due to Doppler would not allow the use of 5G Broadcast modes to vehicles travelling faster than 106 km/h if the required C/N exceeds 10 dB.

If we summarize the results for all three reception modes, we see (Table 25 and Figure 49) that the network would also provide very good coverage for Handheld Indoor reception.

For a required C/N of 10 dB it could serve 92% of the population.

Table 25: Population coverage for Car Mounted, Handheld Indoor and Handheld Outdoor reception using a CP of 300 µs

C/N	Handheld Indoor %	Car Mounted %	Handheld Outdoor %
0 dB	99	99.3	99.3
5 dB	97.9	99.3	99.3
10 dB	92.1	99.3	99

15 dB	70.6	99.2	97.3
20 dB	37.6	98.3	90.1
25 dB	15.8	92.9	66.6

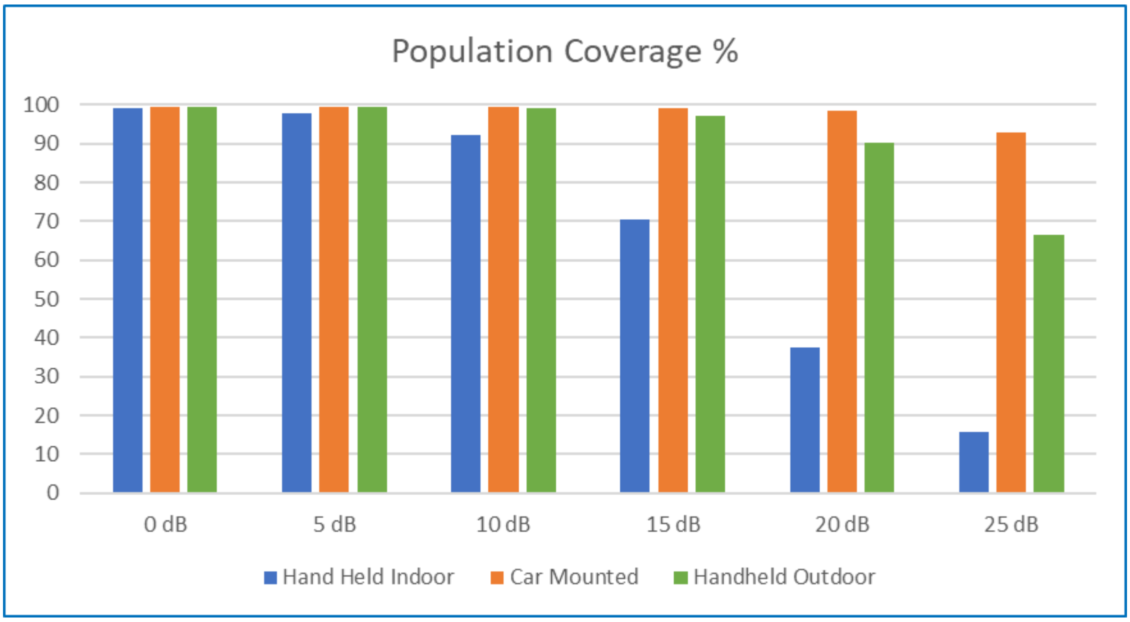


Figure 49: Graphical results for 300 µs CP

We see that Handheld Indoor reception at high C/N is difficult due to the lack of field strength when considering building entry loss. Handheld Outdoor and Car Mounted reception is very good but of course suffers from the receiver speed limitation due to Doppler for Car Mounted reception.

2.2.6 Adding LPLT transmitter in regional SFN

From the earlier simulations we can conclude that a CP of 300 µs will have limitations due to Doppler performance and a CP of 200 µs will provide limited coverage in an SFN. For this reason, a few calculations were also made in a regional SFN, where SFN self-interference has little or no impact when using a CP of 200 µs.

The study was made using the Danish island of Zealand with a size of about 100 km x 100 km and a total population of about 2 million, largely concentrated in the capital city Copenhagen. See Figure 50.

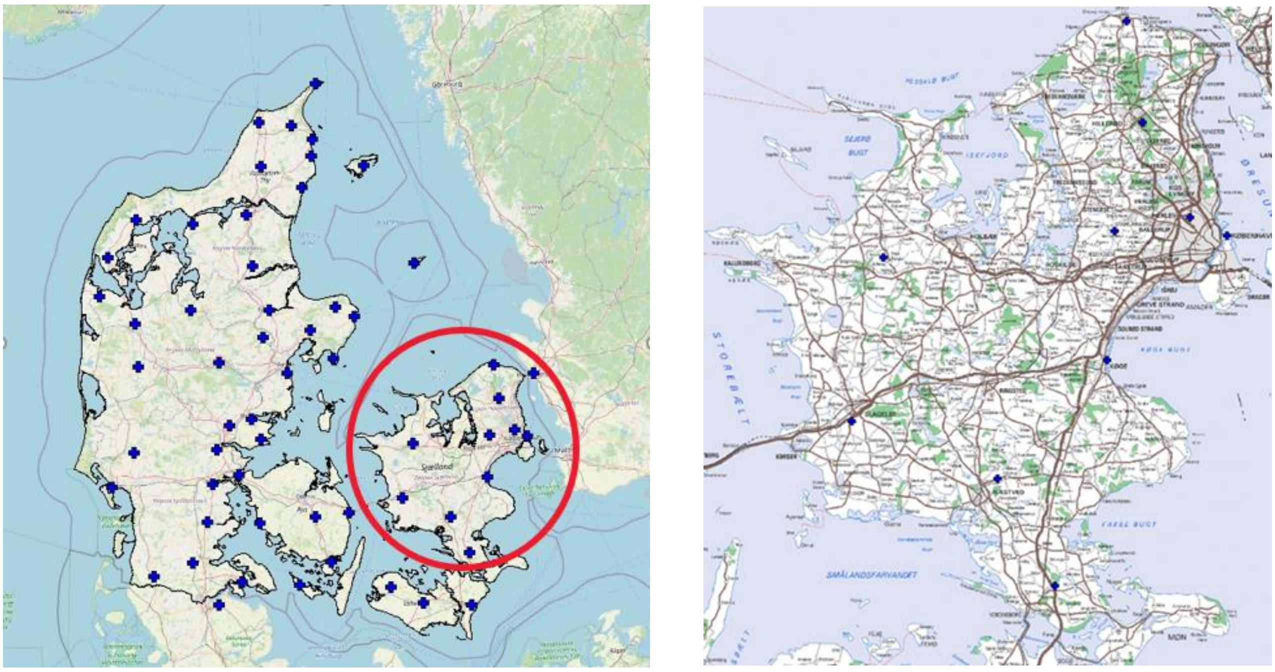


Figure 50: Broadcast Network on the island of Zealand

The existing broadcast infrastructure on Zealand consist of 10 sites, 3 high power sites and 7 medium power sites. As we knew from the earlier work that Handheld Outdoor and Car Mounted reception will be quite good if SFN self-interference can be avoided, we performed the calculations to investigate Handheld Indoor reception. The requirements are as follows:

- Handheld Indoor Service
- C/N 20 dB
- Coverage criteria is 95% of locations
- Cyclic Prefix 200 µs
- Population coverage target is 95% of population

From previous experience we knew that it will be difficult for a broadcast infrastructure to provide Handheld Indoor. To complement the broadcast network, we have “access” to about 900 LTE 700 MHz base stations. Positions are taken from the official site database and whilst antenna heights are not given, we assumed an antenna height of 30 m and an EIRP of 700 W.

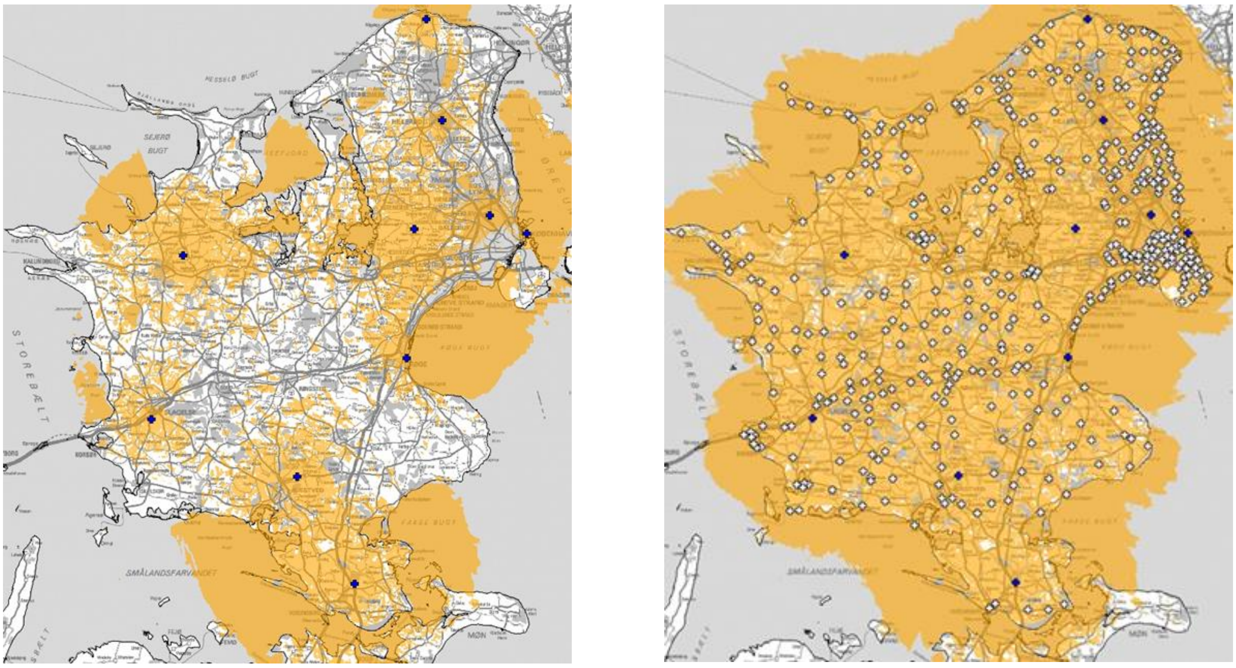


Figure 51: Handheld indoor coverage using only Broadcast network (left) and Broadcast network complemented by 425 Telecom sites (right) to reach the population target of 95%

The broadcast network alone achieves a Handheld Indoor reception of 24% (left map in Figure 51). About 425 additional Telecom sites are needed to reach the 95% population target (right map in Figure 51).

If we now “remove” the broadcast network completely and “rely” only on the 425 telecom sites population coverage will drop to 78%. To again reach the 95% population target there is a need to add about 200 Telecom sites to “replace” the Broadcast network.

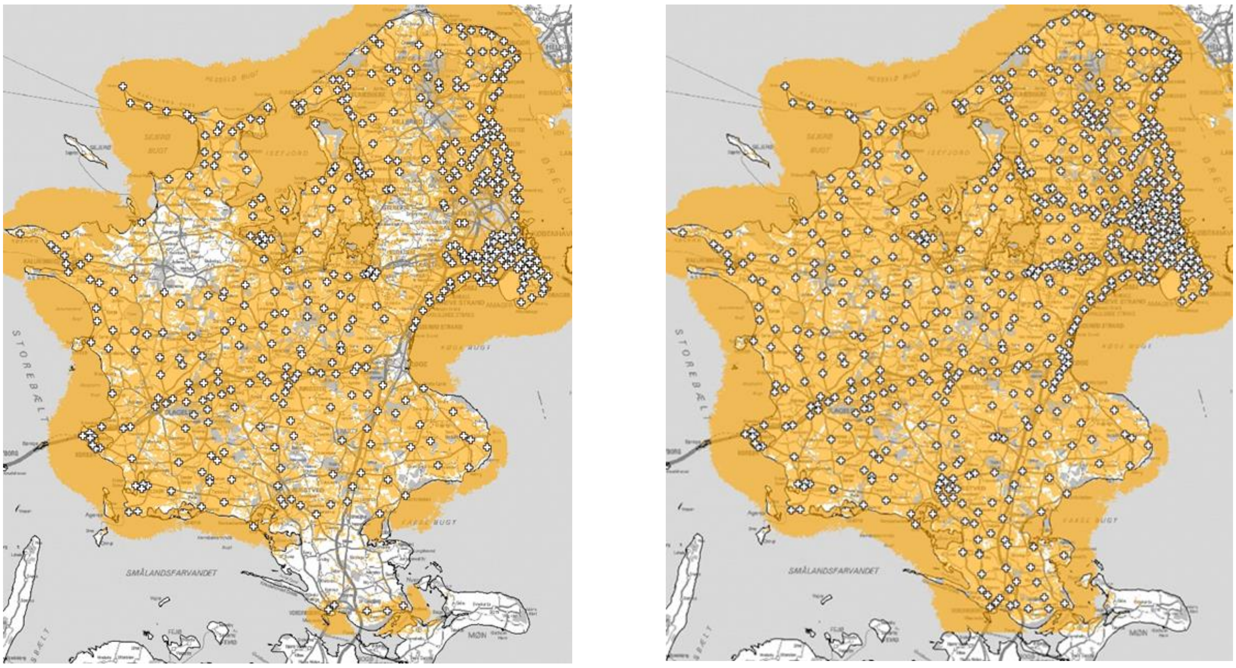


Figure 52: Handheld Indoor coverage using only 425 Telecom sites (left) and when adding 195 to a total of 620 Telecom sites (right) to reach the population target of 95%

In the left map of Figure 52 it can be seen where the Broadcast sites are missing.

Even if the original Handheld Indoor coverage by the broadcast network alone (24%) is low, it still provides quite good “umbrella” coverage in the SFN and almost 200 Telecom sites are needed to replace them.

The results are summarized in Table 26.

Table 26: Summary of results for the regional SFN

Network type	Number of Broadcast sites	Number of Telecom sites	Population coverage HH indoor 95% locations
Broadcast Only	10	-	24%
Broadcast and Telecom	10	425	95%
Telecom (Broadcast removed)	-	425	78%
Telecom Only	-	620	95%

2.2.7 Conclusions

In the study we have simulated LTE based 5G Broadcast coverage for a network based on existing Broadcast infrastructure. The following conclusions may be drawn:

In a large area SFN in flat area with sea paths:

- The Cyclic Prefix of 200 µs is too short. There will be significant limitations due to SFN self-interference
- SFN self-interference is reduced significantly when using a CP of 300 µs. Even system variants requiring a C/N of 20 dB would provide population coverage above 90% for Handheld Outdoor and Car Mounted reception.
- Car Mounted reception using 300 µs CP will be difficult above, say, 100 km/h due to Doppler for system variants which require a C/N above 10 dB

In Regional SFNs:

- Use of 200 µs CP would provide good Handheld Outdoor and Car Mounted reception at C/N of up to 20 dB
- Broadcast networks alone will not provide coverage at high C/N for Handheld Indoor reception
- When combining Broadcast (HP and MP) infrastructure with Telecom sites, broadcast sites may be used to provide significant umbrella coverage in an SFN

3. Overall conclusions

The simulations carried out on theoretical networks as well as those based on real networks in Italy and Denmark (two quite different countries in terms of size and terrain morphology) allow the following conclusions to be drawn:

- Homogeneous[21] HPHT or MPMT[22] networks show good performance for Fixed Roof Top reception, with a relatively low density of transmitters, but have limitations in terms of coverage and available SINR for Car Mounted reception and significant limitations for Handheld Portable reception of 5G Broadcast. In SFN mode, full rural area coverage with HPHT for Car Mounted reception would be possible with SINR of up to 10 dB while MPMT could offer full rural area coverage for Car Mounted reception with up to 15 dB SINR. However, these values would require the use of long CP, preferably 300 µs, which is associated with a long symbol time that limits the maximum achievable speed in Car-Mounted reception due to Doppler effects.
- Homogeneous LPLT networks show good performance for Car Mounted, Handheld Portable and Fixed reception. They can offer full area coverage for Car Mounted reception in urban and suburban environments with up to 25 dB SINR and coverage in the same environments for portable outdoor reception with up to 15 dB SINR. They also work with a lower CP of 100 µs, which is associated with a short symbol time that allows reception at high speeds. However, to achieve such coverage and permit use of the lowest cyclic prefix, they require a high site density.
- Hybrid networks, a mix of HPHT/MPMT/LPLT sites, present the best compromise between performance for Car Mounted and Handheld Portable reception modes in all environments (Rural, Suburban and Urban) and the number of sites required for a given coverage.

Simulations on theoretical hybrid HPHT/MPMT networks show that full rural area coverage for Car Mounted reception with SINR of 15 dB in 5 MHz can be obtained with a site density of around 22 sites per 10000 km^2.

In urban and suburban areas, additional MPMT or LPLT sites will be needed. According to simulations on LPLT networks in urban and suburban areas, full area coverage for Car Mounted and Handheld Portable outdoor reception with SINR of up to 25 dB in 5 MHz can be obtained with 3 km inter-site distance. Such inter-site distance corresponds to a site density of 1284 sites per 10000 km^2. However, from the two real case studies described in this report, it may be deduced that an optimized selection of all site types can significantly reduce the required site density, compared to full LPLT network, particularly by basing the selection of LPLT sites on high population density areas and main transportation routes.

The choice of the CP acts on two issues in an opposing manner. On one side a shorter CP, say 100 µs, helps to achieve higher speed in mobile reception but does not allow mitigation of self-interference inside large SFNs using HPHT sites. On the other hand, a larger CP, such as 300 µs significantly mitigates the self-interference in large SFNs of HPHT sites but restricts the speed in mobile reception, due to the Doppler effect.

Simulations on theoretical networks showed that a CP of 200 µs would be a suitable compromise between coverage and mobility. This CP allows mobile reception at 600 MHz with a maximum speed

[21] Homogeneous means that only one type of site is used in the network.

[22] HPHT: High Power High Tower networks.

MPMT: Medium Power Medium Tower networks.

LPLT: Low Power Low Tower networks.

The characteristics of these networks are defined in Annex A.

of up to around 200 km/h for a SINR of 15 dB. While this CP is largely sufficient for LPLT networks (which can work even with 100 µs CP), the simulations showed that a CP of 200 µs allows high coverage rates for Hybrid HPHT and MPMT networks in rural areas for mobile reception with a SINR of 15 dB with suitable EIRP adjustments.

The real case study in Italy showed that a Hybrid HPHT/LPLT network can give good coverage for mobile reception with a SINR of 15 dB using a CP of 200 µs with the necessary network optimisation to reduce the self-interference in the SFN.

The second real case study, on Denmark, showed that 200 µs CP is suitable for a Hybrid HPHT/MPMT/LPLT Single Frequency Network covering a region of about 100 km x 100 km for Handheld Indoor reception and Car-Mounted reception at a SINR of up to 20 dB. However, for a national SFN composed of a mixture of HPHT and MPMT sites aiming at offering a SINR of up to 20 dB for Car-Mounted and up to 10 dB for Handheld indoor reception, it showed that a 300 µs CP would be needed to sufficiently mitigate the SFN self-interference.

Regardless of the network configuration, the simulation on theoretical networks showed that it is not possible to operate SFNs using the same frequency in two contiguous regions or countries with different editorial contents while providing contiguous coverage across the borders. In these border areas full coverage requires the use of MFNs. The studies showed that planning MFNs using clusters of SFNs with frequency reuse 3 or 4 achieves the required coverage. This configuration combines the benefits of SFN network gain with a sufficiently large co channel separation distance.

In terms of achievable bitrates for 5G Broadcast in Car-Mounted mobile and Handheld Portable reception, analysis of from the results of the studies described in this report shows that up to 7 Mbit/s in 5 MHz could be achieved with a SINR of 15 dB and a 200 µs CP.

In carrying out these studies, several questions have arisen that will need to be answered as part of further work. The studies are based on standard broadcaster assumptions. These include height loss and standard deviation associated with location variation and the effect of polarisation of the transmission antenna with respect to the receiving system. These could have a significant impact on predicted coverage. Given there is divergent information available on the appropriate values to use, the validity of applying these standard broadcaster assumptions to any studies aimed at assessing coverage to mobile and handheld devices needs to be investigated.

Verification of these assumptions plus the results of ongoing and future trials of 5G Broadcast networks will help to confirm the current conclusions.

Future studies should consider enhancement techniques for mobile reception, such as time-interleaving. It would be also worth investigating closed SFNs[23] using the same frequency across border areas to mitigate the need for MFNs.

[23] A Closed SFN uses directional antenna patterns at transmitters located at its edge, oriented towards the centre of the SFN, to reduce the outgoing interference to neighbouring co-channel networks.

4. References / Bibliography

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[2] EBU Tech 3348. Frequency and network planning aspects of DVB-T2

[3] EBU S-SPT Docs 377, 378 and 379 eMBMS simulator description

[4] 5G X cast Deliverable D3.1 LTE--Advanced Pro Broadcast Radio Access Network Benchmark v1.1, 29/06/2018

[5] 3GPP TS 36.214, v14.0.0, 2016--09, 'Technical Specification Group Radio Access Network; E--UTRA;Physical Layer; Measurements Release 14

[6] Monte Carlo based time variation of signals in broadcast network simulations - Simon Elliott & David Vargas (BBC), Jordi Giménez (IRT), Assunta De Vita (RAI), Alberto Rico-Alvariño & Amer Catovic (Qualcomm Inc.), Richard Rudd (Plum Consulting/ITU SG3), Erik Stare (Ericsson) - EBU Technical Review February 2020.

[7] Receiving Antenna Alignment in Hexagonal Grid Simulations - Simon Elliott (BBC), Jordi Joan Gimenez (IRT), Assunta De Vita (RAI), David Vargas (BBC) - A Study for LTE-based 5G Terrestrial Broadcast - EBU Technical Review February 2020.

[8] 'Redundancy on Demand – Extending the Coverage Area of Terrestrial Broadcast via Broadband Networks', J. Qi, J. Zollner, J. Robert, L. Stadelmeier and N. Loghin, IEEE Transactions on Broadcasting, Vol. 60, No.2, June 2014.

[9] 'Field Trial of a Redundancy on Demand DVB-T2 System', F. Schreiber, J. Zollner, L. Stadelmeier, R. Burow, F. Kattanek, S. Krueger, IEEE 2016.

[10] OFDM Receivers – impact on coverage of inter--symbol interference and FFT window positioning, R. Brugger (IRT), D. Hemingway (BBC), EBU Tech Review 295, 30 July 2003

[11] ITU Document 6A/198 - Liaison statement to Working Party 6A - Report on the work of Correspondence Group 3K-4 concerning the correlation of short term interfering signals, 11 March 2013

[12] TG6(14)070Rev2, 'The relationship between ISD and SINR in LTE eMBMS networks for fixed rooftop reception', 13 May 2014

[13] EBU S-SPT Document 413 – 5G-Broadcast LPLT sites

[14] Performance of 5G Broadcast and benefits of proposed time--interleaving enhancements, David Vargas, Simon Elliott, Oliver Haffenden, Ryan McCartney, Andrew Murphy (all BBC), Jordi Joan Jimenez (5G MAG) – IBC Technical Paper, 14 September 2020.

[15] LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer procedures - 3GPP TS 36.213 version 16.3.0 Release 16 / ETSI TS 136 213 V16.3.0 (2020-11)

[16] Equalization of FFT-leakage in mobile DVB-T. Master Thesis in Radiocommunication from the Royal Institute of Technology, Stockholm performed at TERACOM AB, Stockholm, Sweden by Guillaume Geslin - April 1998.

Annex A: Simulation parameters for 5G Broadcast generic network simulations

Where applicable, the following parameters are defined for a working frequency centred on 600 MHz.

A1. Time percentage of signals

Where only location variation is considered, wanted signals are predicted using 50% of time curves from Recommendation ITU-R P.1546-5; unwanted signals are predicted using 1.75% of time curves, to account for a simplified model for correlation between interfering signals as advised by ITU-R WP6A in document 6A/198 / Simple method.

In the case of location and time variation simulations, wanted and unwanted signals are predicted using a time varying propagation model (Recommendation ITU-R P.1546-5 extended beyond its [1-50]% validity domain to [0-100]% of time by extrapolation), with a target availability of 99% of time.

A2. 5G Broadcast system parameters

Table A1 describes the valid combination of system parameters for 5G Broadcast data signals: CAS signalling can only use variant 1, while the useful payload (carried by the PMCH – Physical Multicast Channel) may adopt any variant from 2 to 6. Those parameters were derived from 3GPP TS36.211 v16.1.0 (2020-03) “E-UTRA Physical channels and modulation (Release 16)”.

Table A1: 5G Broadcast system parameters

Variant	Carrier Spacing delta f [kHz]	Subcarriers / RB	OFDM symbols / subframe	Tu (µs)	#Tu samples	CP (µs)	#CP samples	Ts (µs)	CP Ratio	Dx	Dy	Nyquist factor	Nyquist limit (µs)	EI- Equalisation interval / Tp[24] (µs)
1	15.00	12	14	66.7	2044	4.7	144	71.40	5/71	3	5	1/3	22.23	19.80
2	15.00	12	12	66.7	2045	16.7	512	83.40	1/4	1	4	1	66.70	59.40
3	7.50	24	6	133.3	4099	33.3	1024	166.60	1/4	2	2	1/2	66.65	59.36
4	1.25	144	1	800	24576	200	6144	1000.00	1/4	3	1	1/3	266.67	237.50
5	2.50	72	2	400	12288	100	3072	500.00	1/4	2	1	1/2	200.00	178.13
6	0.37	486	1	2700	82944	300	9216	3000.00	1/9	3	1	1/3	900.00	801.56

Note: in COFDM based broadcasting systems with fixed bandwidth, an FFT size is specified. In 5G Broadcast system, as the channel width can vary, no FFT size is specified, but rather a carrier spacing:

100 µs CP → 2.5 kHz carrier spacing

200 µs CP →1.25 kHz carrier spacing

300 µs CP →0.37 kHz carrier spacing

[24] Equalization interval duration is usually taken as 57/64 of the Nyquist limit to reflect real implementation of receivers.

As a comparison, if we consider a 5 MHz channel in 5G Broadcast, with 25 Resource Blocks (180 kHz / RB), the above figures would correspond to 2K / 4K / 13.5K FFT respectively.

A3. Reception parameters

Table A2 deals with the reception parameters used in the simulations for each of the agreed scenarios, with the following additional assumptions:

The receiver and transmitters are assumed to use the same polarization; hence no polarization discrimination is assumed.

The receiver and the transmitter are considered as being in the same environment; the receiver clutter height depends on the environment as follows:

Clutter height = 10 m for a Rural or Suburban environment

Clutter height = 20 m for an Urban environment

Clutter height = 30 m for a Dense Urban environment (only for reference, not considered in the simulations)

Table A2: Reception parameters used in the simulations for each of the agreed scenarios

Scenarios	1	2	3	4	5	6
Reception parameters	Car mounted (CM)	Handheld In-Car	Handheld portable outdoor	Fixed rooftop (FRT)	Portable indoor (PI)	Handheld portable indoor (P-H/Internal Antenna)
Type of reception	Mobile	Mobile	Portable	Fixed	Portable	Portable
Path type	Land	Land	Land	Land	Land	Land
Receiver antenna gain, including possible body loss and receiver diversity gain (dBi)	3	-5.8	-5.8	13	1.7	-5.8
Entry loss (dB) – Building/vehicle	0	9	0	0	11	11
Standard deviation associated with entry loss (dB)	0	5	0	0	6	6
Receiver height (m)[25]	1.5	1.5	1.5	10	1.5	1.5
Receiver feeder loss (dB)	0	0	0	4	0	0
Other losses[26] (dB)	1	1	1	1	1	1
Receiver strategy for signals from the same SFN	Maximum C/I					
Location variation standard deviation (dB)	5.5					
Receiver Noise Figure (dB)	6	9	9	6	9	9

[25] Received field strength is predicted using the ITU-R Recommendation P.1546-5 model at the specified receiver height, considering the receiver clutter height corresponding to the receiver environment (rural, suburban, urban). At 600 MHz, for rural environment, this corresponds to a height loss of 16.8 dB, for suburban environment to a height loss of 17 dB and for urban environment to a height loss of 23.3 dB for a 1.5 m reception height when compared to the reception at the height of the representative receiver clutter height of the corresponding environment.

[26] Other losses account for implementation losses (front-end performances). There could be other losses related to the performance of the transmitter, like Error Vector Magnitude for LPLT transmitters, but these are not considered in this study.

Percentage of locations to protect on a small area[27]	95%	95%	95%	95%	95%	95%

A4. Transmission parameters

Three network types were agreed for the modelling of 5G Broadcast networks:

Network type 1: High Power High Tower (HPHT)

Network type 2: Medium Power Medium Tower (MPMT)

Network type 3: Full cellular / Low Power Low Tower (LPLT)

Note: antenna polarization has no incidence on simulation as both the transmitter and receiver are assumed to use the same polarization. This parameter is not described in the following paragraphs.

As the parameters for modelling the HPHT and MPMT networks are taken from real-life broadcast deployments, all the EIRP values reported in the following paragraphs are referenced by convention to an 8 MHz bandwidth (7.77 MHz effective channel). To use those EIRP values for a precise 3GPP bandwidth, a specific correction factor must be applied as described in § A4.5.

A4.1 Network type 1 parameters - HPHT

Table A3 describes the parameters used for the modelling of HPHT networks. Annex B provides useful analysis of inter-site distance of HPHT networks in Sweden, France and the United Kingdom

Table A3: Parameters used for the modelling of HPHT networks

Network type	HPHT
Inter-Site Distance (km) – ISD	50, 60, 70, 80, 100, 120
EIRP (dBm)	76, 79, 82, 85[28]
Antenna height above ground level (m)	200, 300, 350
Tilt (° positive below horizontal)	1, 2, 3°[29]
Environment type	Rural
Clutter height (m)	10

A4.2 Network type 2 parameters - MPMT

Table A4: Parameters used for the modelling of MPMT networks

Network type	MPMT
Inter-Site Distance (km) – ISD	20, 30, 40, 50
EIRP (dBm)	62, 69, 72[30]
Antenna height above ground level (m)	80

[27] For mobile and portable reception, the percentage of locations to protect on a small area can also include 70%, 90% and 99%; for fixed reception, 90% can also be considered.

[28] Corresponding to 25 kW, 50 kW and 100 kW ERP respectively.

[29] Vertical antenna pattern according to ITU-R BT.2337 High Power for DVB-T/DVB-T2.

[30] Corresponding to 1 kW, 5 kW and 10 kW ERP respectively.

Tilt (° positive below horizontal)	0° [31]
Environment type	Rural
Clutter height (m)	10

A4.3 Network type 3 parameters – LPLT

Report ITU-R M.2292 has been used as the source to identify Low Power Low Tower network parameters (shown in Table A5).

Table A5: Parameters used for the modelling of LPLT networks – M.2292

Network type	Full cellular - LPLT		
Environment type	**Rural**	**Suburban**	**Urban**
Inter-Site Distance (km) – ISD[32]	12	3	3
EIRP (dBm)[33]	57.4 / 59.4	57.4 / 59.4	57.4 / 59.4
Antenna height above ground level (m)	30	30	30
Tilt (° positive below horizontal)	3° [34]		
Clutter height (m)	10	10	20

A4.4 Reference vertical radiation patterns

The following figure illustrates the resulting vertical radiation patterns considered in the simulations according to the selected parameters.

Note: the MPMT vertical radiation pattern is given for reference only, as for MPMT no vertical radiation pattern is considered.

[31] No vertical antenna pattern.

[32] Calculated from a specified cell radius > 5 km (8 km typical) for macro rural scenario and 0.5 - 5 km (2 km typical) for macro urban/suburban scenario.

[33] 57.4 dBm corresponds to approximately 550 W EIRP. This value is derived from Base station EIRP/sector of 58 dBm in 10 MHz, with 0.6 dB reduction for the 8/10 MHz ratio. A 3 dB reduction is specified in ITU-R M.2292 to take account of an average base station activity factor of 50%; this reduction is not applied in the case of 5G Broadcast as the system is always active.

[34] Recommendation ITU-R F.1336 (equation 1d) with 9.1 degrees 3 dB beamwidth in the elevation plane and k = 0.3.

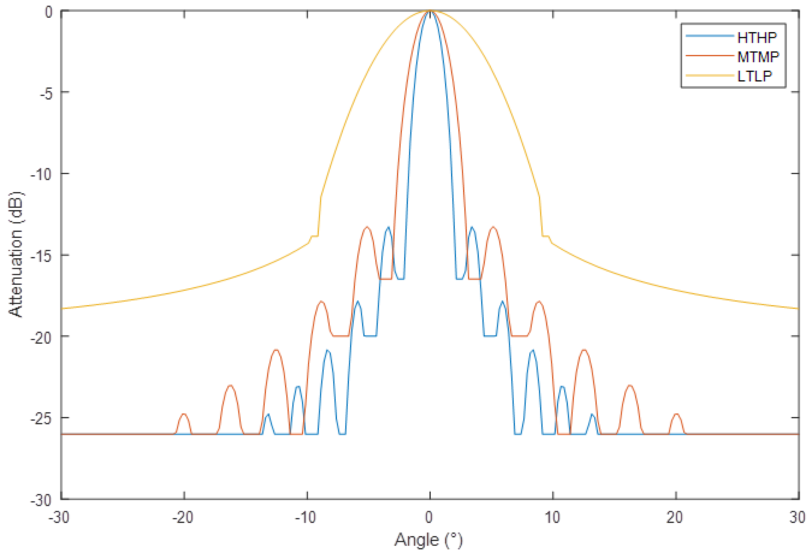


Figure A1: Vertical radiation patterns for the different types of networks (without tilt)

A4.5 Correction factor with respect to the channel bandwidth

When considering a different channel bandwidth, and more specifically in the case of 3GPP agreed system bandwidth, a correction must be applied to the EIRP values to keep the EIRP / MHz constant, as well as the resulting signal-to-noise ratio (SNR) in case the bandwidth is changed. The corresponding correction is given in the table below.

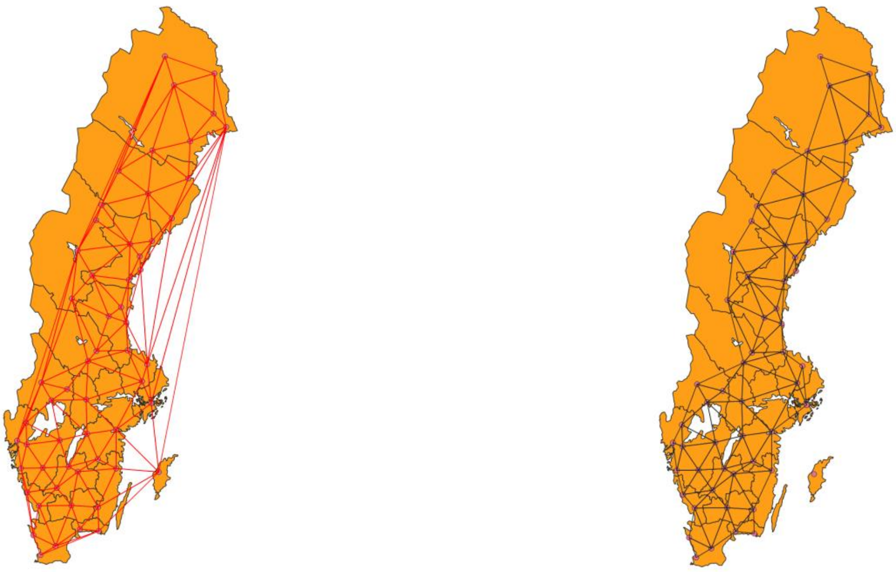
Table A6: EIRP correction factor depending on channel bandwidth

Channel BW (MHz)	1.4	3	5	10	15	20
Effective BW (MHz)	1.08	2.7	4.5	9	13.5	18
Correction factor (dB)	-8.6	-4.6	-2.4	0.6	2.4	3.6

Annex B: Inter Site Distance

To better understand the inter-site distance of HPHT networks, an analysis of such sites in Sweden, France and the United Kingdom was carried out. Given coordinates of sites, the distance to the nearest neighbours can be derived using Delaunay triangulation.

Care needs to be taken to filter (to remove false, not valid) sides of the generated triangles, illustrated in Figure B1. In the case of Sweden, with the false sides included, the average ISD for the 57 HPHT sites is 105 km, removing false sides the ISD reduces to 93 km, see Figure B2.



Full Delaunay Triangulation Filtered Delaunay Triangulation

Figure B1: ISD of HPHT Sites in Sweden

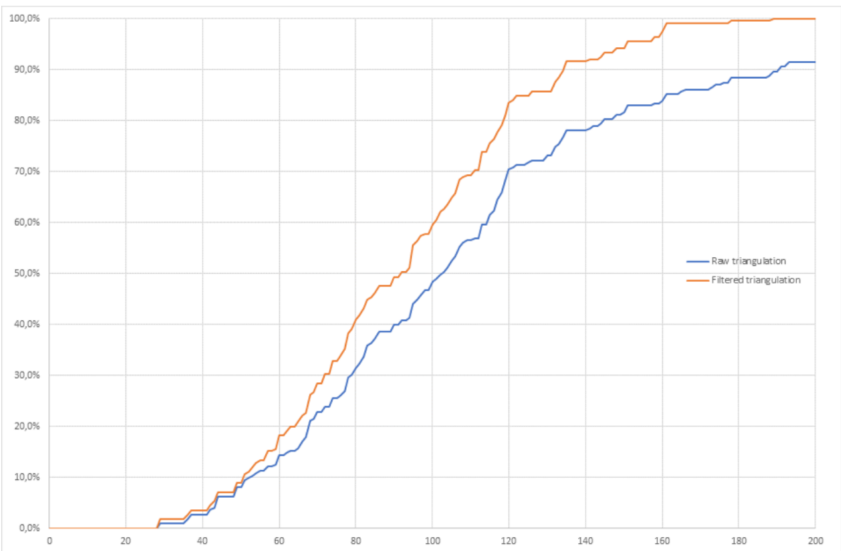


Figure B2: CDF of HPHT ISD in Sweden

Triangulation for the 112 main French sites with false links at the edge removed, Figure B3, provides a median ISD value of 82 km, Figure B4. Terrain and population play a part in the site spacing. Low ISD values can be found in Paris, the Alps and the Jura, high ISD values around Toulouse Pic-du-Midi (Southeastern France).

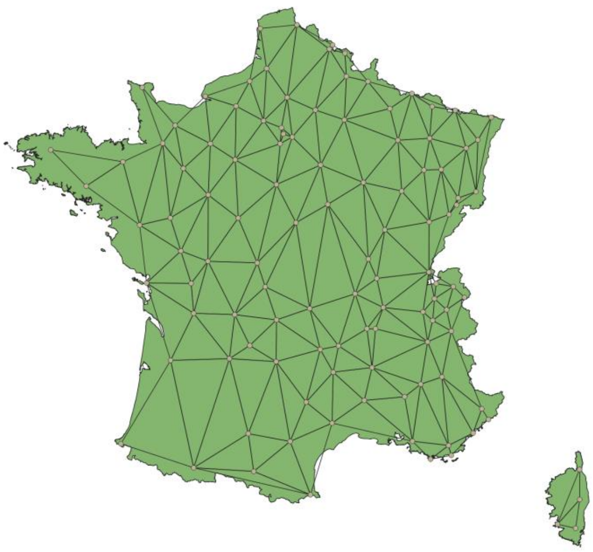


Figure B3: ISD of HPHT Sites in France

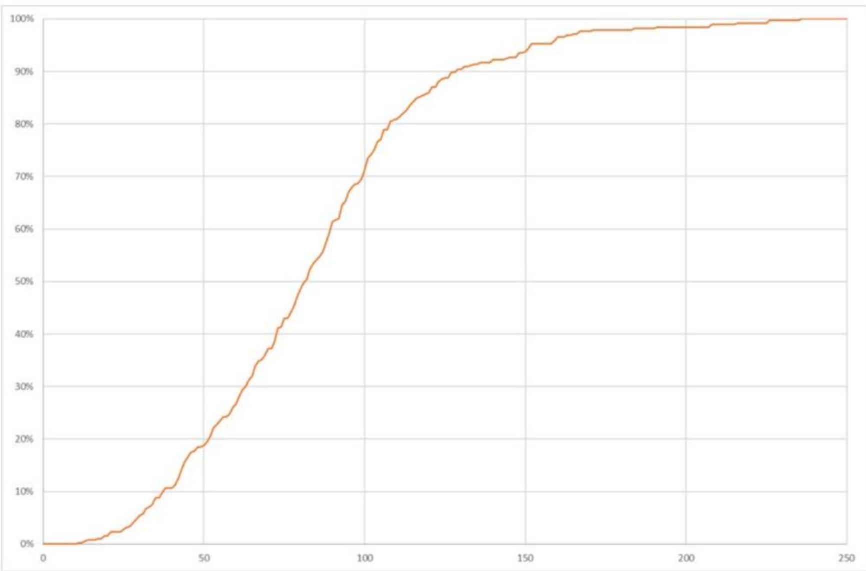


Figure B4: CDF of HPHT ISD France

Triangulation for the 50 main UK sites with links over 100 km removed provides a median ISD value of 73 km, see Figure B5.

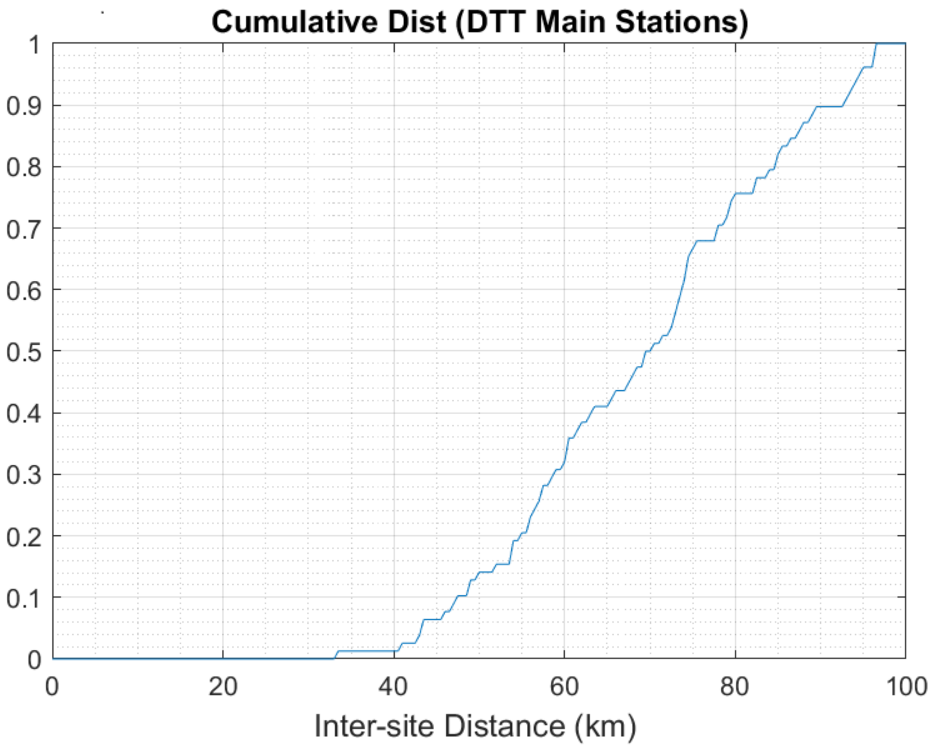


Figure B5: CDF of HPHT ISD United Kingdom

Taking the results for Sweden, France and the United Kingdom and recognising that there is a spread in results and that values for other countries may differ significantly, for generic studies an ISD for HPHT sites of 80 km could be used.

Annex C: Results of coverage simulations at national or regional borders

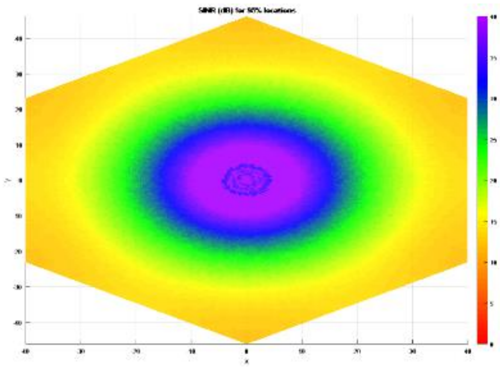
C1. HPHT results

The scenario is based on a HPHT network topology with the following characteristics:

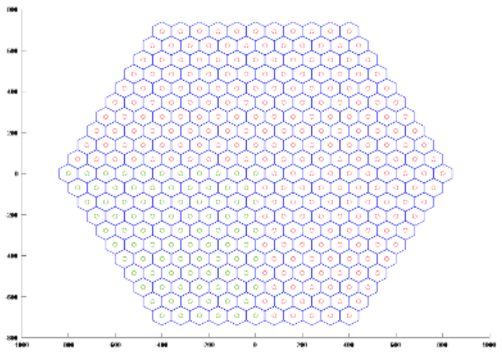
- Rural reception
- 80 km ISD
- 300 m antenna height
- 2° antenna tilt
- 79.6 dBW EIRP
- 300 µs Cyclic Prefix duration

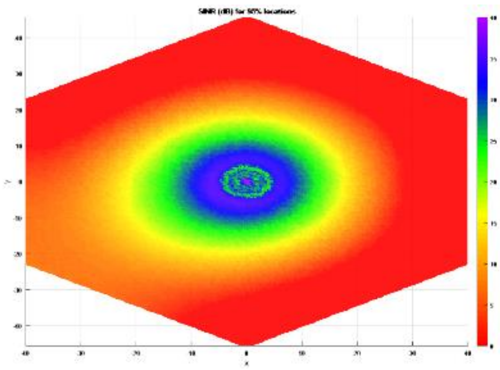
C1.1 Corner regional boundary results

Original situation (no boundaries)

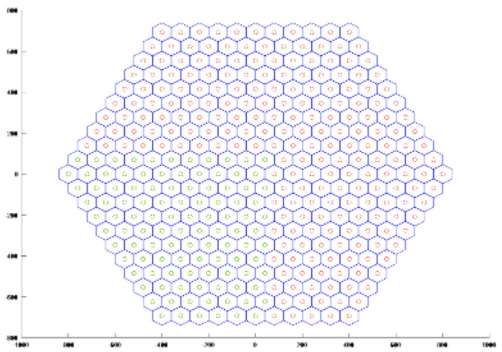


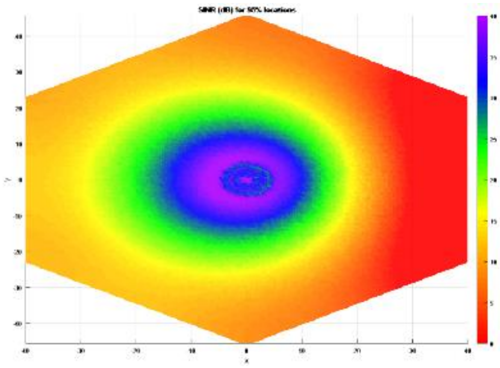
Corner – 0 ISD



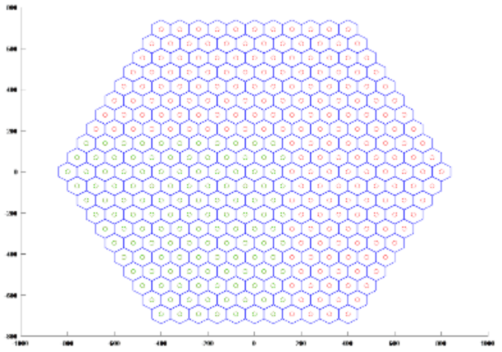


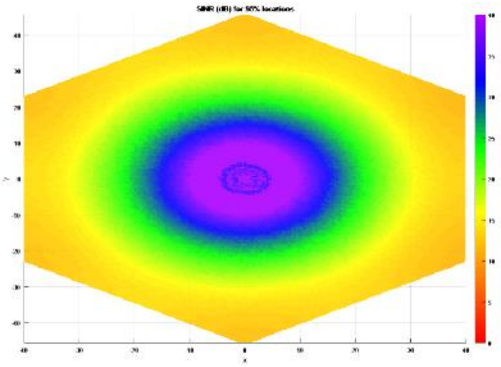
Corner – 1 ISD





Corner – 2 ISD





The following figure compares the resulting complementary CDF of SINR for the 4 situations presented above.

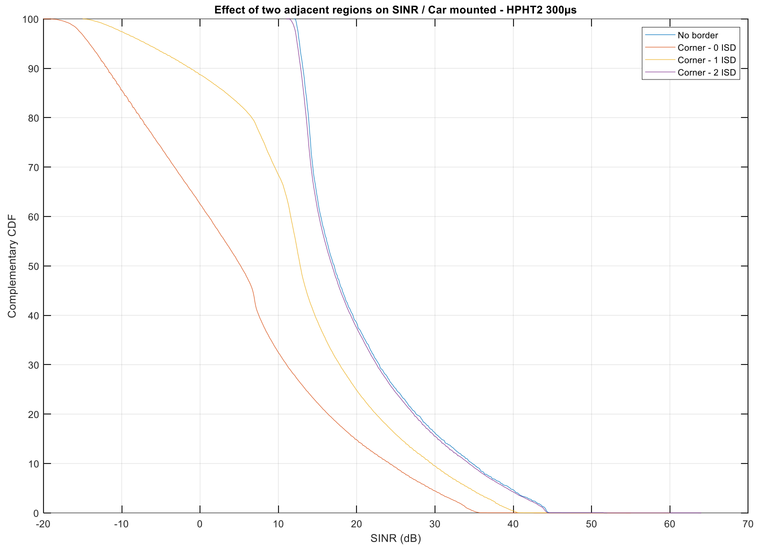
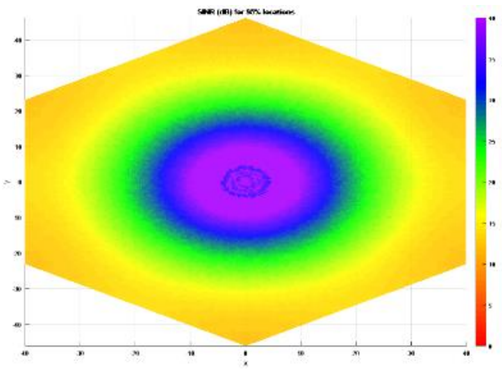


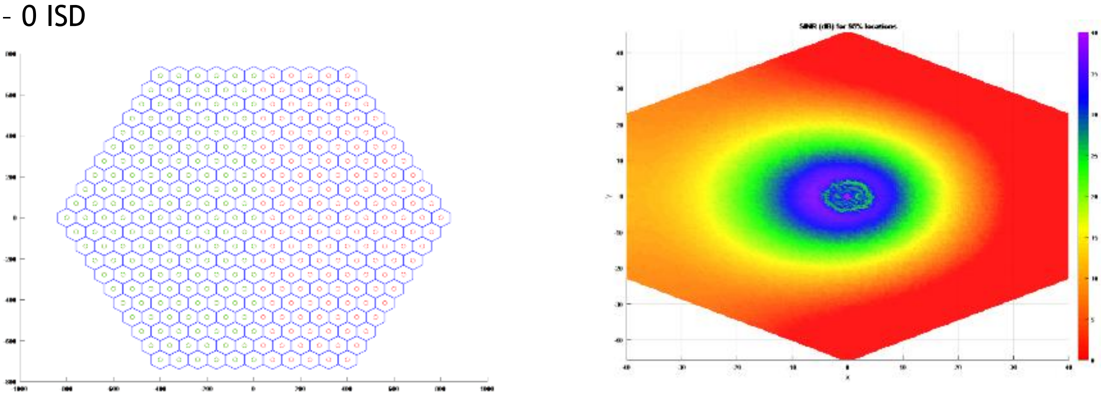
Figure C1: Corner regional boundary results for HPHT

C1.2 Straight regional boundary (East/West separation)

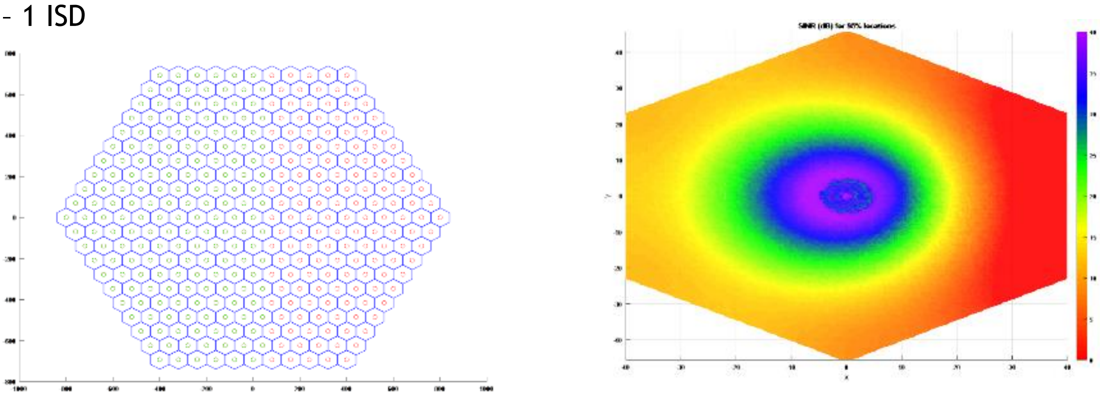
Original situation (no boundaries)



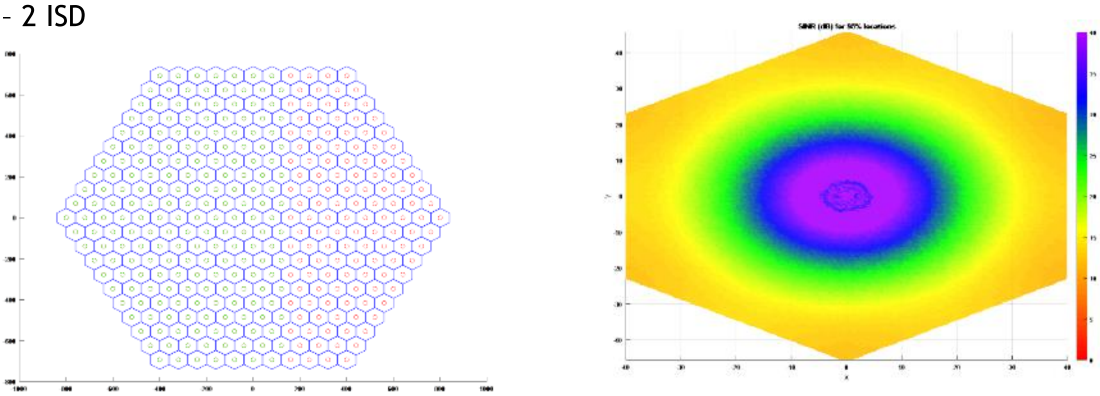
E/W – 0 ISD



E/W – 1 ISD



E/W – 2 ISD



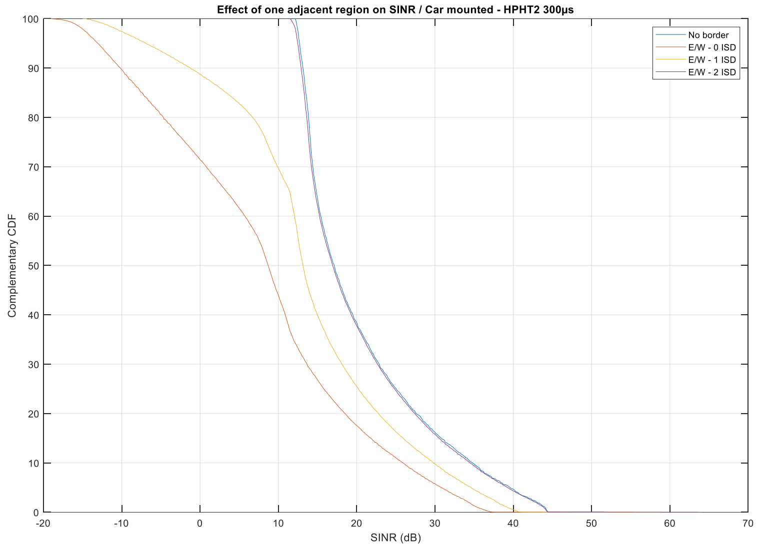
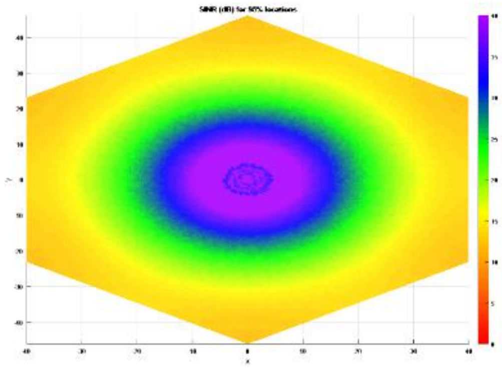


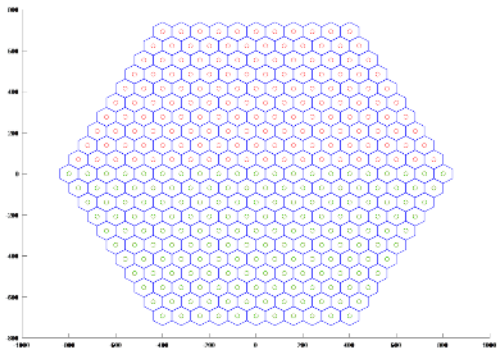
Figure C2: Straight E/W boundary region results comparison for HPHT

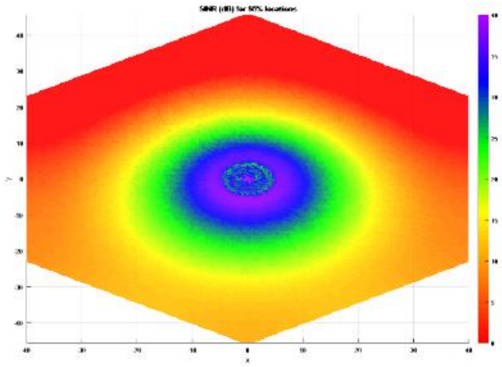
C1.3 Straight regional boundary results (North/South separation)

Original situation (no boundaries)

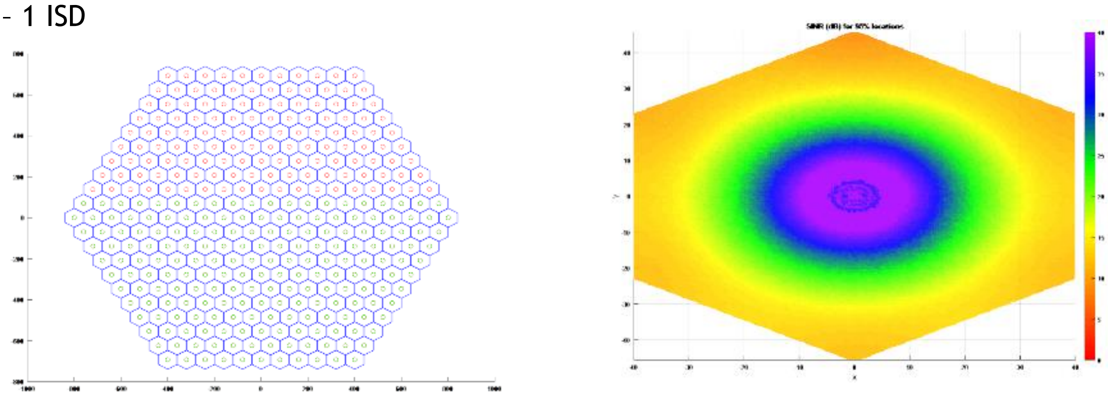


N/S – 0 ISD

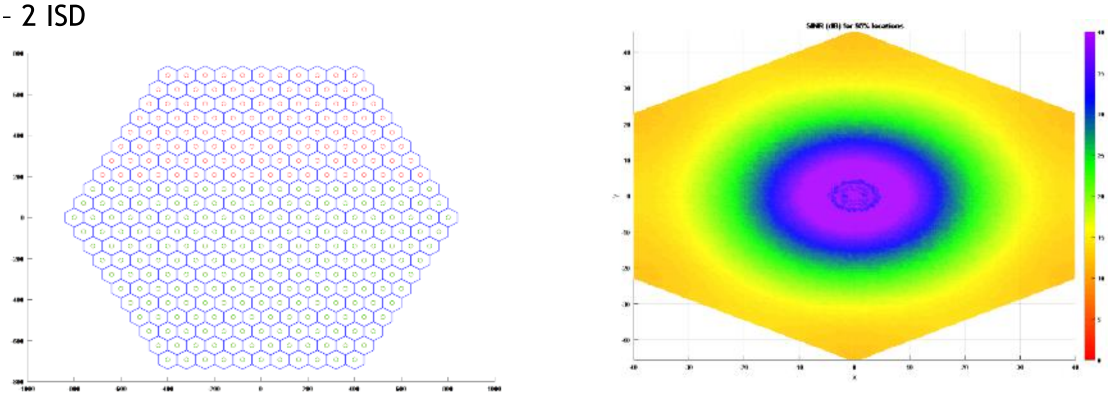




N/S – 1 ISD



N/S – 2 ISD



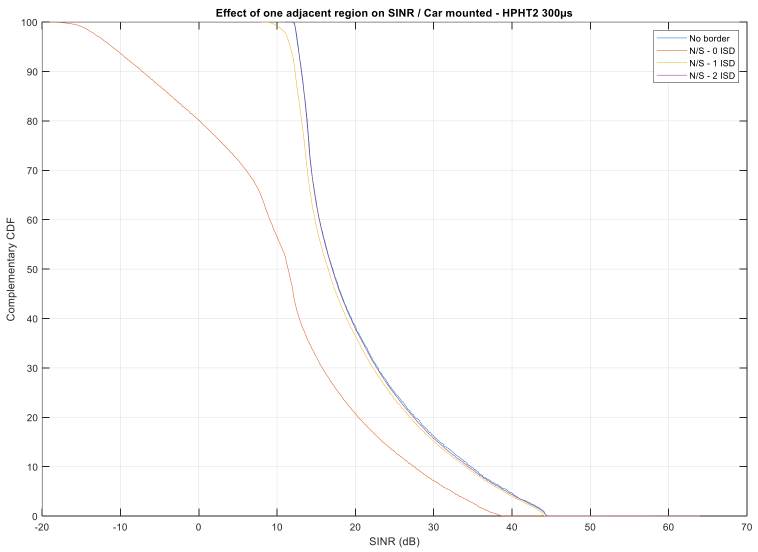


Figure C3: Straight N/S boundary region results comparison for HPHT

C2. MPMT results

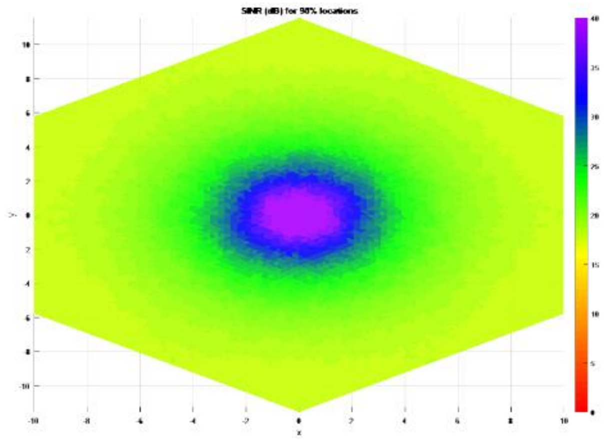
The scenario is based on a MPMT network topology with the following characteristics:

- Rural reception.
- 20 km ISD.

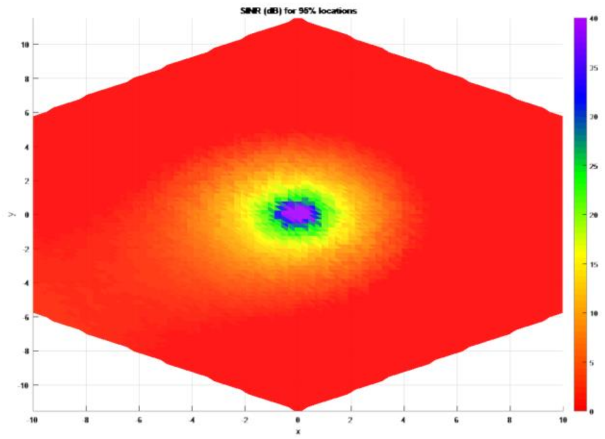
- 80 m antenna height.
- no antenna tilt (and no vertical pattern).
- 59.6 dBW EIRP.
- 300 µs Cyclic Prefix duration.

C2.1 Corner regional boundary results

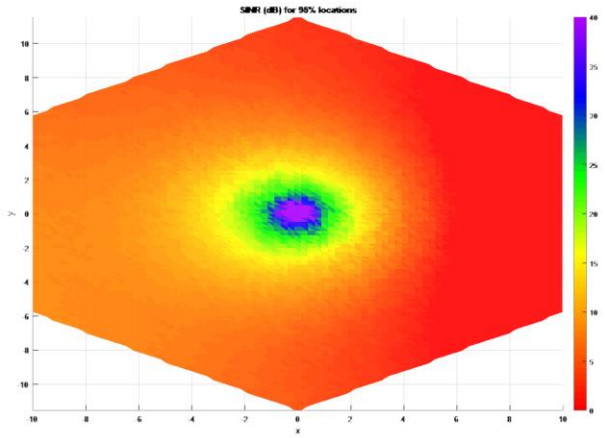
Original situation (no boundaries)



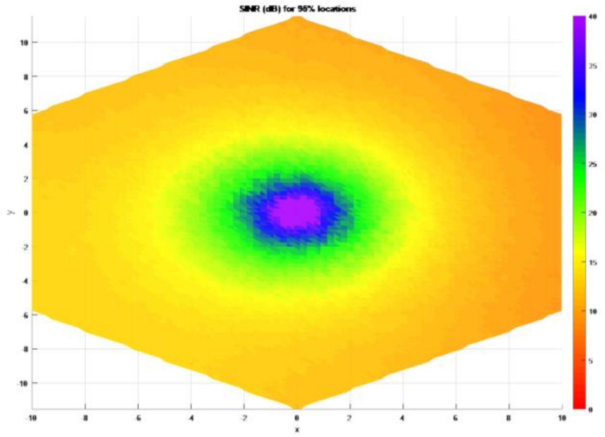
Corner – 0 ISD



Corner – 1 ISD



Corner – 2 ISD



The following figure compares the resulting complementary CDF of SINR for the 4 situations presented above.

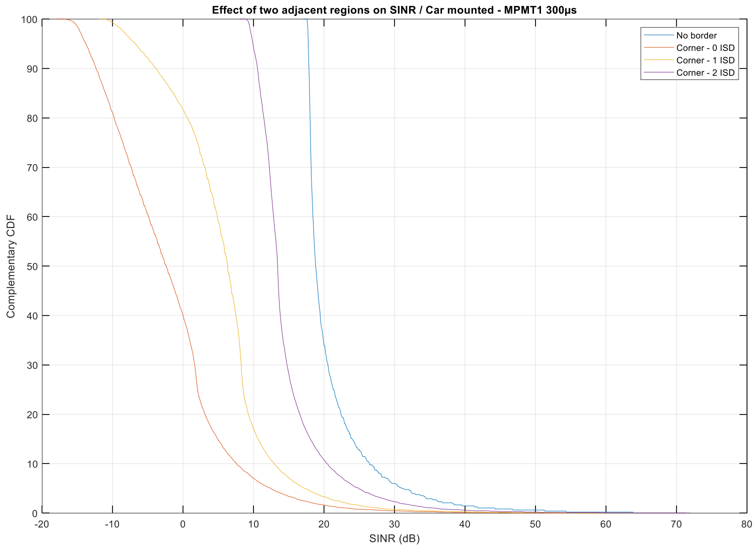
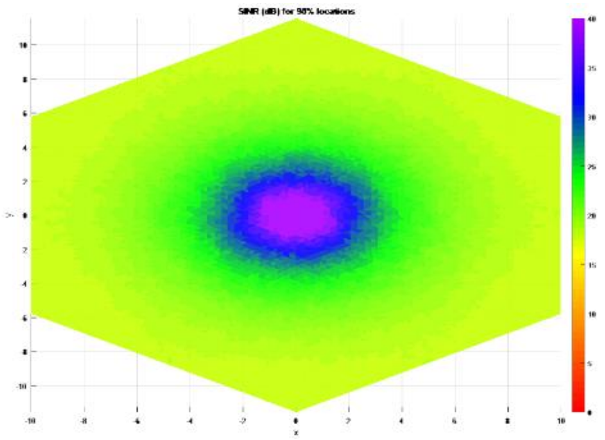


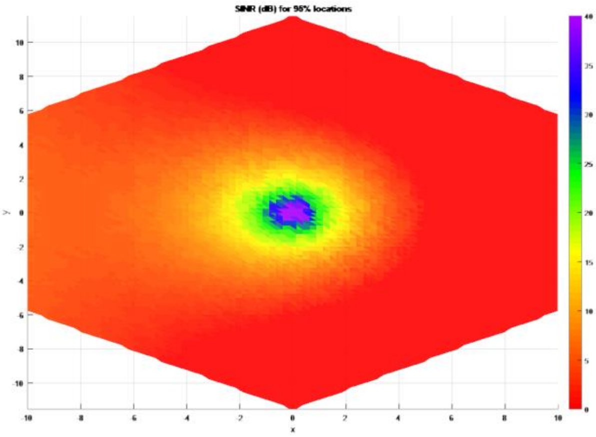
Figure C4: Corner regional boundary results for MPMT

C2.2 Straight regional boundary (East/West separation)

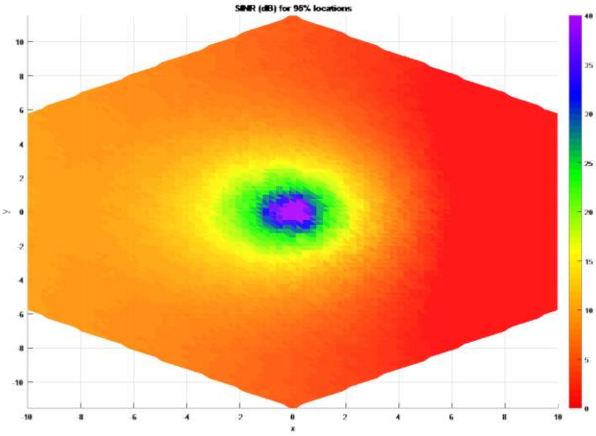
Original situation (no boundaries)



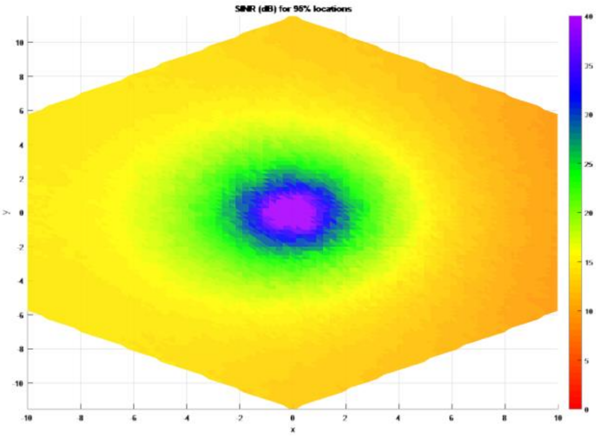
E/W – 0 ISD



E/W – 1 ISD



E/W – 2 ISD



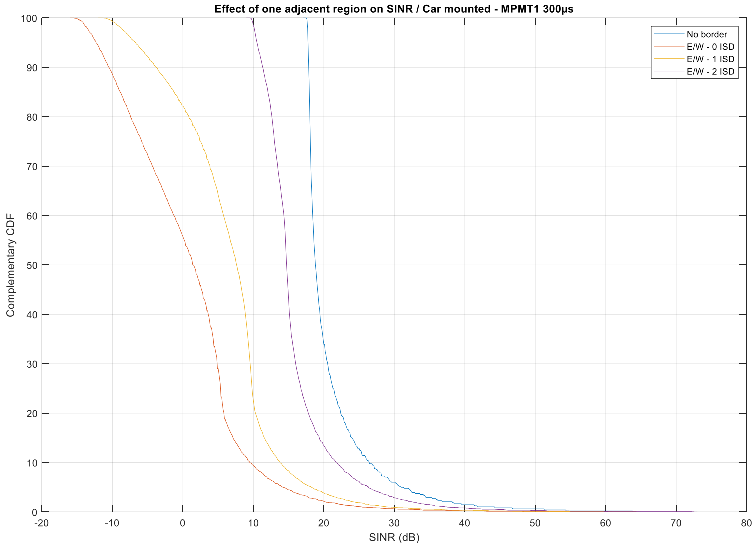
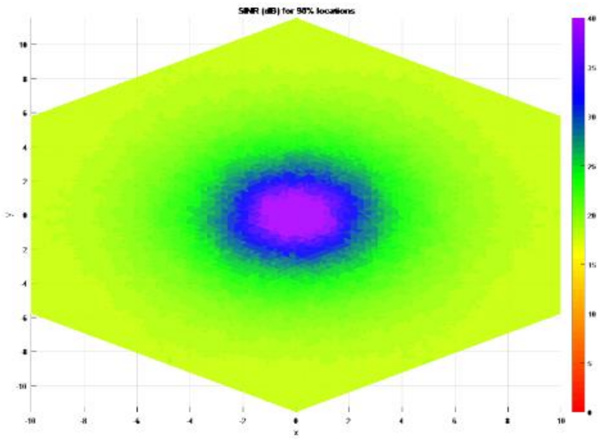


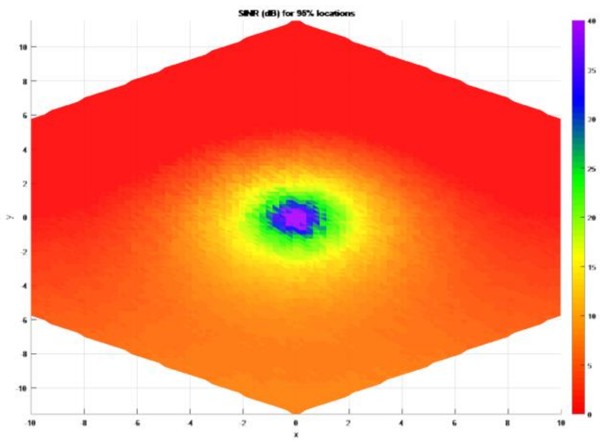
Figure C5: Straight E/W boundary region results comparison for MPMT

C2.3 Straight regional boundary results (North/South separation)

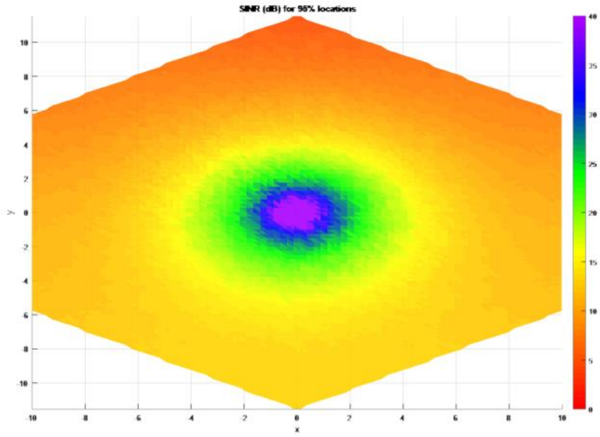
Original situation (no boundaries)



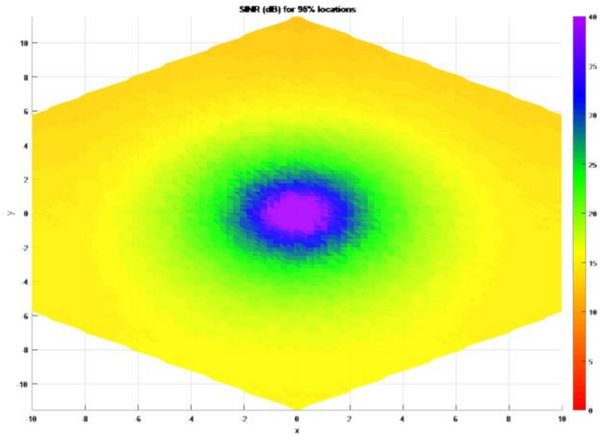
N/S – 0 ISD



N/S – 1 ISD



N/S – 2 ISD



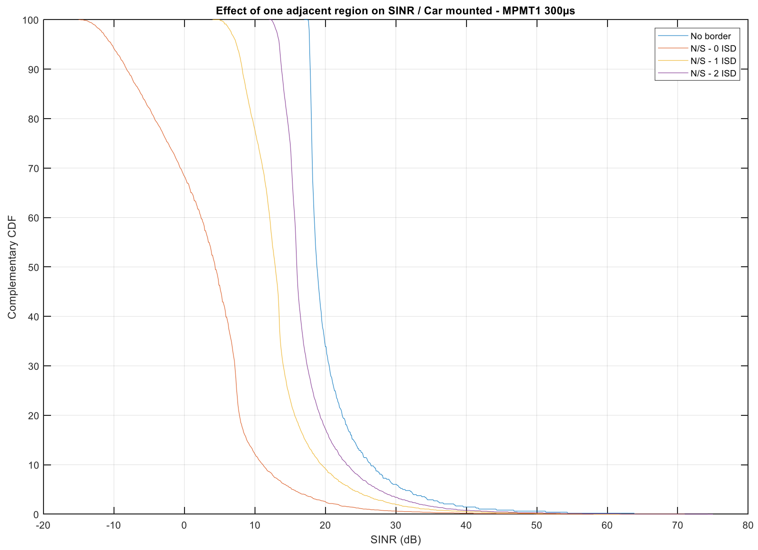


Figure C6: Straight N/S boundary region results comparison for MPMT

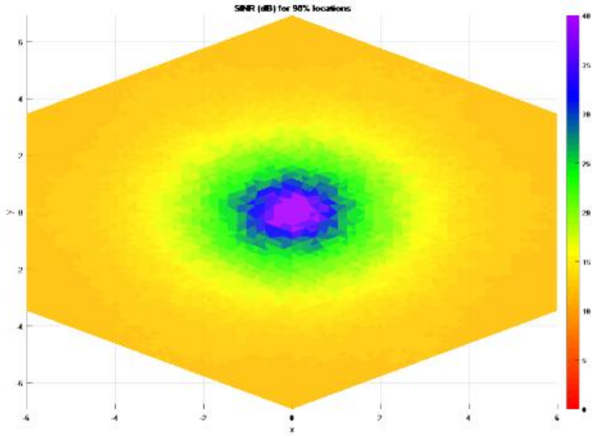
C3. LPLT results

The scenario is based on a LPLT network topology with the following characteristics:

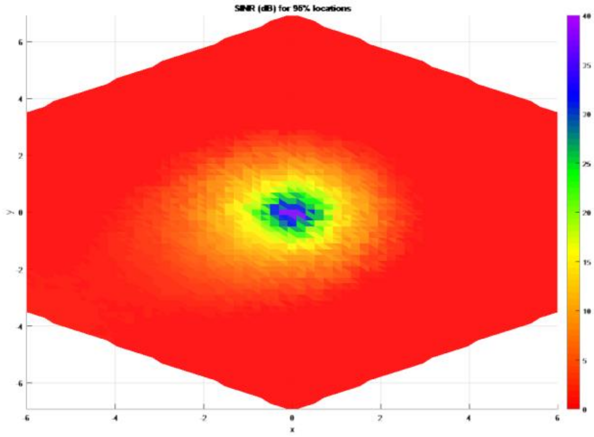
- Rural reception.
- 12 km ISD.
- 30 m antenna height.
- 3° antenna tilt.
- 57 dBW EIRP.
- 100 µs Cyclic Prefix duration.

C3.1 Corner regional boundary results

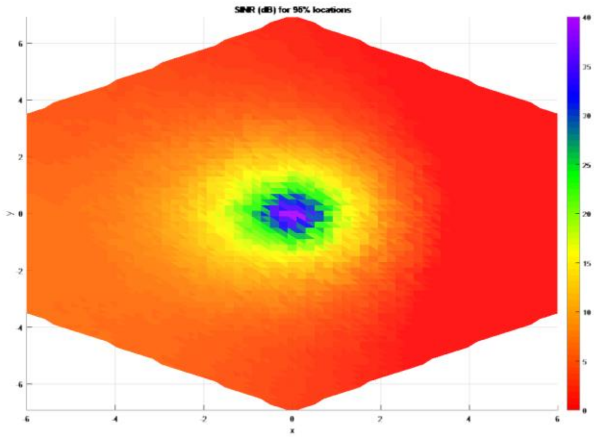
Original situation (no boundaries)



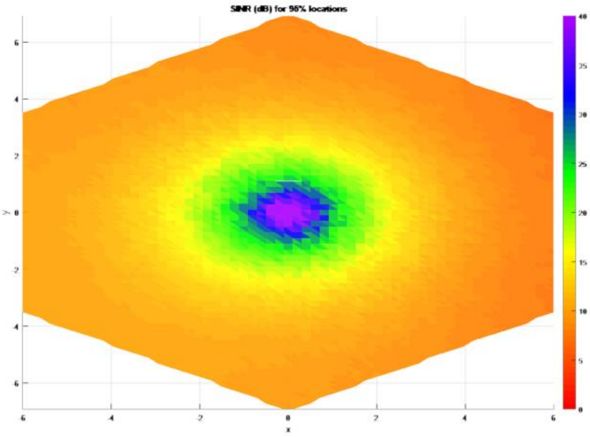
Corner – 0 ISD



Corner – 1 ISD



Corner – 2 ISD



The following figure compares the resulting complementary CDF of SINR for the 4 situations presented above.

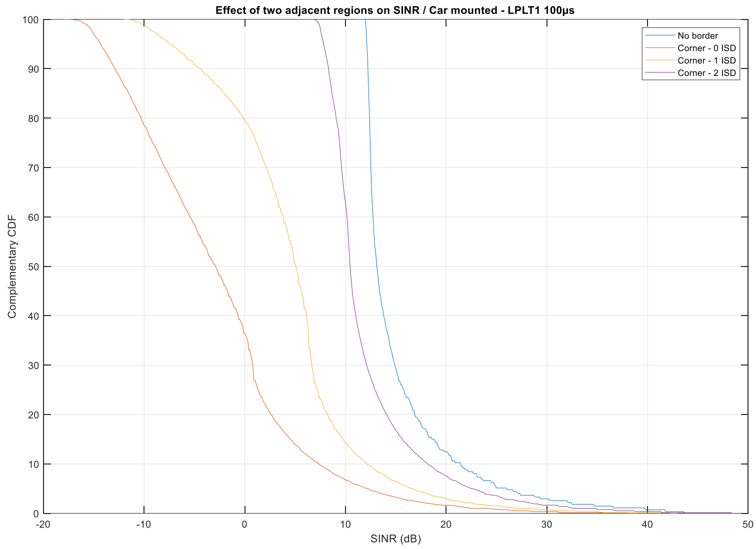
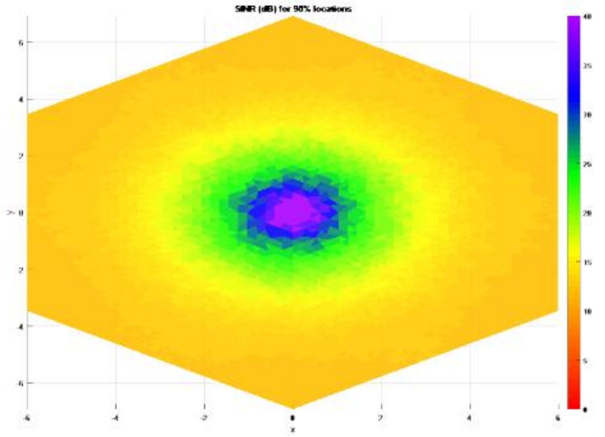


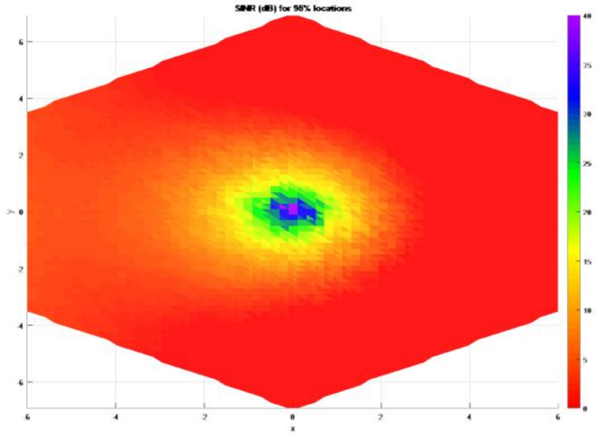
Figure C7: Corner regional boundary results for LPLT

C3.2 Straight regional boundary (East/West separation)

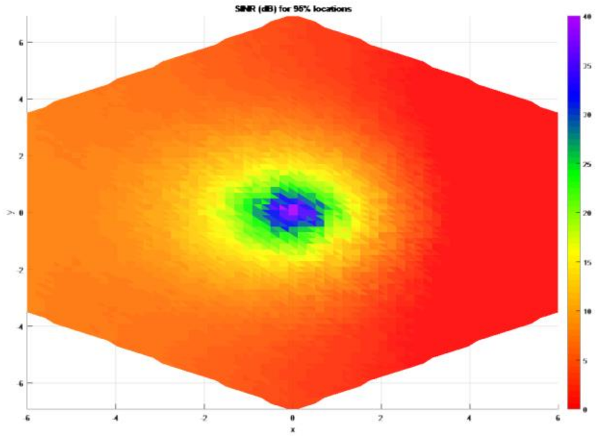
Original situation (no boundaries)



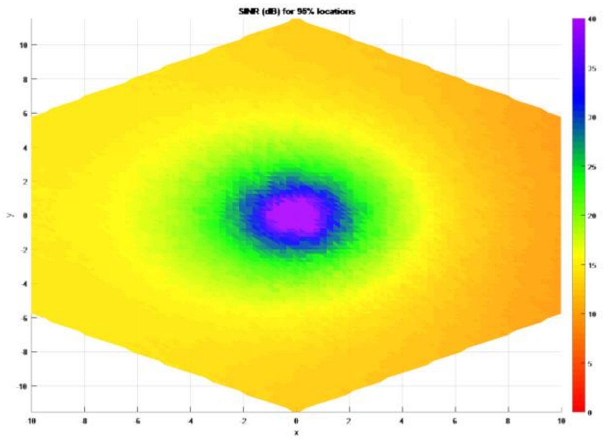
E/W – 0 ISD



E/W – 1 ISD



E/W – 2 ISD



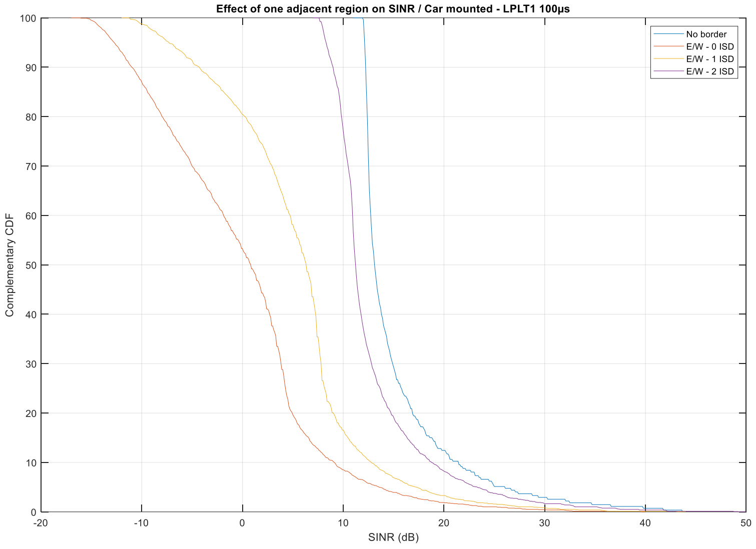
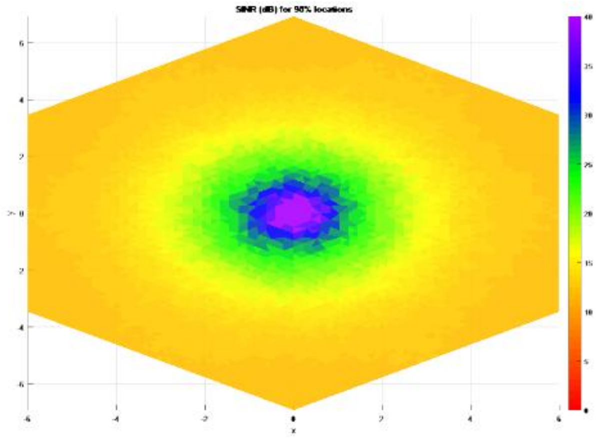


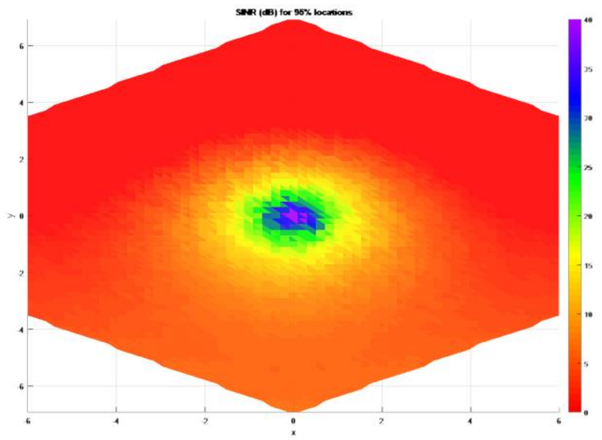
Figure C8: Straight E/W boundary region results comparison for LPLT

C3.3 Straight regional boundary results (North/South separation)

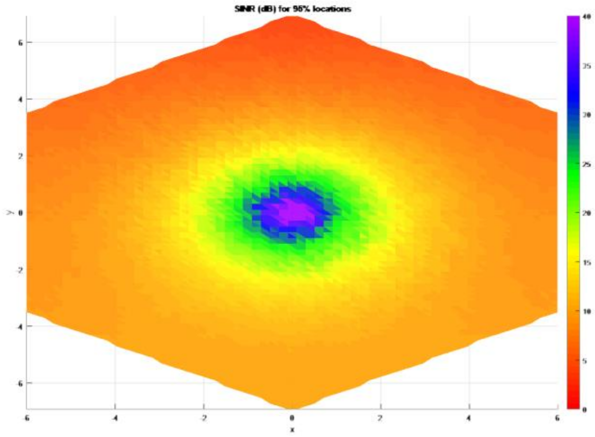
Original situation (no boundaries)



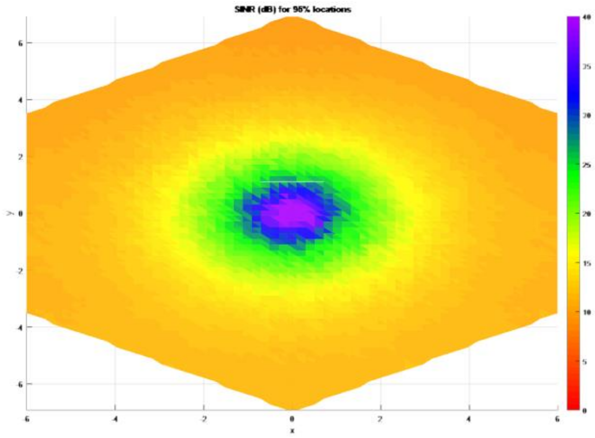
N/S – 0 ISD



N/S – 1 ISD



N/S – 2 ISD



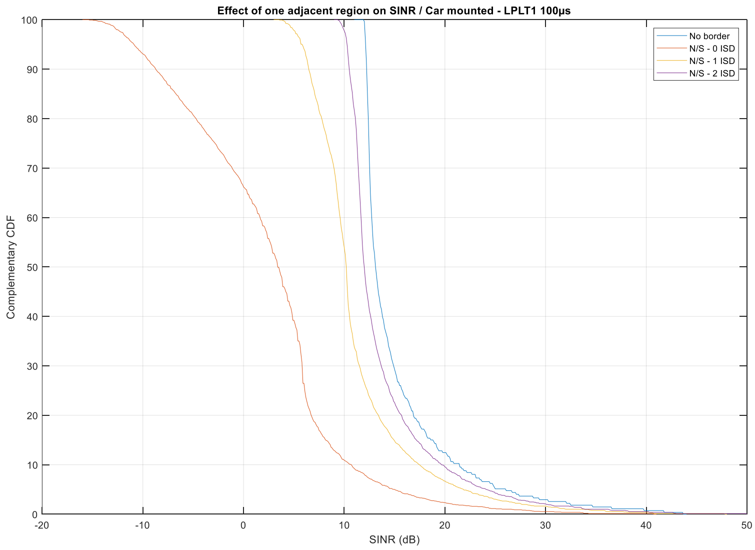


Figure C9: Straight N/S boundary region results comparison for LPLT

Annex D: Capacity versus SINR mapping

Tables D1, D2 & D3 provide an indicative mapping of the 5G Broadcast system capacity with the corresponding signal-to-Interference-plus-noise-ratio (SINR) in various reception environments, for a 5 MHz channel. They are based on the recent results relative to link-level simulations of different 5G Broadcast configurations presented in the IBC Paper [14] for the SINR values.

The 5 MHz channel capacity for the different MCS (Modulation and Coding Schemes) configurations permitted by the 5G Broadcast system were derived from 3GPP TS 36.213 version 16.3.0 Release 16 [15]. As the capacity slightly varies with the number of resource blocks used in the 3GPP system (data mapping varies with the number of resource blocks, see § 11 of the 3GPP TS 36.213 document), the corresponding values differ slightly from the IBC Paper, as this last one is based on 10 MHz channels. In addition, only the information regarding SINR values without possible time-interleaving enhancements are presented here, as time-interleaving is not a standardized 3GPP feature for the time being.

Table D1: SNR to capacity mapping for 100 µs CP

MCS Index	MOD	COD	Raw Spectral Efficiency (b/s/Hz)	Effective Spectral Efficiency (b/s/Hz)	Capacity (Mbit/s) In 5 MHz channel	Fixed SINR (dB)	Portable SINR (dB)	Mobile SINR (dB)
0	QPSK	0.126	0.252	0.133	0.663			
1	QPSK	0.167	0.335	0.176	0.881			
2	QPSK	0.203	0.406	0.214	1.069			
3	QPSK	0.262	0.524	0.276	1.381			
4	QPSK	0.333	0.667	0.351	1.755		3.6	3.8
5	QPSK	0.410	0.821	0.432	2.161		4.6	4.6
6	QPSK	0.481	0.963	0.507	2.535		5.6	5.8
7	QPSK	0.576	1.153	0.607	3.034		7	7.2
8	QPSK	0.647	1.295	0.682	3.409		7.8	8.2
9	QPSK	0.742	1.484	0.782	3.908		9.2	9.6
10	16-QAM	0.371	1.484	0.782	3.908		8.2	8.6
11	16-QAM	0.407	1.627	0.856	4.282		9	9.4
12	16-QAM	0.460	1.840	0.969	4.844		10	10.4
13	16-QAM	0.531	2.124	1.119	5.593		11.2	11.4
14	16-QAM	0.598	2.391	1.259	6.295		12.4	12.8
15	16-QAM	0.669	2.676	1.409	7.043		13.2	13.8
16	16-QAM	0.716	2.865	1.509	7.543		14.2	14.8
17	64-QAM	0.478	2.865	1.509	7.543		14.4	15
18	64-QAM	0.493	2.960	1.558	7.792		15	15.6
19	64-QAM	0.564	3.387	1.783	8.915		16.4	17
20	64-QAM	0.612	3.671	1.933	9.664		17.4	18.6
21	64-QAM	0.659	3.956	2.083	10.413		18.4	19.8

22	64-QAM	0.707	4.240	2.232	11.162		19.6	21.2
23	64-QAM	0.776	4.658	2.452	12.262		21.6	25
24	64-QAM	0.836	5.013	2.640	13.198		26.4	
25	64-QAM	0.871	5.227	2.752	13.759		28	
26	64-QAM	0.942	5.653	2.976	14.882			
27	64-QAM	0.978	5.867	3.089	15.444			
28	256-QAM	0.733	5.867	3.089	15.444			
29	256-QAM	0.760	6.080	3.201	16.006			
30	256-QAM	0.813	6.507	3.426	17.129			
31	256-QAM	0.849	6.791	3.576	17.878			
32	256-QAM	0.919	7.351	3.870	19.352			
33	256-QAM	0.954	7.636	4.020	20.101			
34	256-QAM	0.990	7.920	4.170	20.849			

Table D2: SNR to capacity mapping for 200 μs CP

MCS Index	MOD	COD	Raw Spectral Efficiency (b/s/Hz)	Effective Spectral Efficiency (b/s/Hz)	Capacity (Mbit/s) In 5 MHz channel	Fixed SINR (dB)	Portable SINR (dB)	Mobile SINR (dB)
0	QPSK	0.113	0.227	0.133	0.663			
1	QPSK	0.151	0.301	0.176	0.881			
2	QPSK	0.183	0.365	0.214	1.069			
3	QPSK	0.236	0.472	0.276	1.381			
4	QPSK	0.300	0.600	0.351	1.755			
5	QPSK	0.369	0.739	0.432	2.161	4	4	4.6
6	QPSK	0.433	0.867	0.507	2.535	4.8	5	5.6
7	QPSK	0.519	1.037	0.607	3.034	6	6.2	6.8
8	QPSK	0.583	1.165	0.682	3.409	6.8	7	7.8
9	QPSK	0.668	1.336	0.782	3.908	8	8.2	9
10	16-QAM	0.334	1.336	0.782	3.908	7.8	7.8	8.4
11	16-QAM	0.366	1.464	0.856	4.282	8.4	8.4	9.2
12	16-QAM	0.414	1.656	0.969	4.844	9.2	9.2	10.2
13	16-QAM	0.478	1.912	1.119	5.593	10.4	10.4	11.4
14	16-QAM	0.538	2.152	1.259	6.295	11.6	11.4	13
15	16-QAM	0.602	2.408	1.409	7.043	12.4	12.4	14
16	16-QAM	0.645	2.579	1.509	7.543	13.2	13	15.2
17	64-QAM	0.430	2.579	1.509	7.543	13.8	13.4	15.8
18	64-QAM	0.444	2.664	1.558	7.792	14.4	14.4	17
19	64-QAM	0.508	3.048	1.783	8.915	15.6	15.4	19.6
20	64-QAM	0.551	3.304	1.933	9.664	16.8	16.4	22.8
21	64-QAM	0.593	3.560	2.083	10.413	17.8	17.2	
22	64-QAM	0.636	3.816	2.232	11.162	19.4	18.2	

23	64-QAM	0.699	4.192	2.452	12.262	22.8	21.8	
24	64-QAM	0.752	4.512	2.640	13.198			
25	64-QAM	0.784	4.704	2.752	13.759			
26	64-QAM	0.848	5.088	2.976	14.882			
27	64-QAM	0.880	5.280	3.089	15.444			
28	256-QAM	0.660	5.280	3.089	15.444			
29	256-QAM	0.684	5.472	3.201	16.006			
30	256-QAM	0.732	5.856	3.426	17.129			
31	256-QAM	0.764	6.112	3.576	17.878			
32	256-QAM	0.827	6.616	3.870	19.352			
33	256-QAM	0.859	6.872	4.020	20.101			
34	256-QAM	0.891	7.128	4.170	20.849			

Table D3: SNR to capacity mapping for 300 µs CP

MCS Index	MOD	COD	Raw Spectral Efficiency (b/s/Hz)	Effective Spectral Efficiency (b/s/Hz)	Capacity (Mbit/s) In 5 MHz channel	Fixed SINR (dB)	Portable SINR (dB)	Mobile SINR (dB)
0	QPSK	0.091	0.182	0.132	0.658			
1	QPSK	0.122	0.245	0.177	0.887			
2	QPSK	0.145	0.291	0.211	1.053			
3	QPSK	0.191	0.383	0.277	1.386			
4	QPSK	0.240	0.481	0.348	1.739			
5	QPSK	0.301	0.603	0.436	2.181			
6	QPSK	0.347	0.695	0.503	2.514	3.6	4	
7	QPSK	0.428	0.855	0.619	3.097	4.6	4.8	
8	QPSK	0.479	0.959	0.694	3.471	5.2	5.6	
9	QPSK	0.548	1.097	0.794	3.970	6	6.4	
10	16-QAM	0.582	2.327	0.842	4.212	6.8	7.2	
11	16-QAM	0.291	1.164	0.842	4.212			
12	16-QAM	0.330	1.319	0.955	4.774			
13	16-QAM	0.381	1.526	1.104	5.522	8.6	8.8	
14	16-QAM	0.428	1.713	1.240	6.201	9.8	9.8	
15	16-QAM	0.480	1.920	1.390	6.950	10.2	10.6	
16	16-QAM	0.514	2.058	1.490	7.449	10.8	11	
17	64-QAM	0.532	3.190	1.540	7.699	11.6	11.8	
18	64-QAM	0.615	3.687	1.779	8.897	12.8	13	
19	64-QAM	0.658	3.946	1.904	9.521	13.6	13.6	
20	64-QAM	0.712	4.270	2.061	10.304	14.6	14.8	
21	64-QAM	0.474	2.847	2.061	10.304	15	14.8	
22	64-QAM	0.509	3.053	2.211	11.053	15.8	15.6	
23	64-QAM	0.567	3.402	2.463	12.314	17.2	16.8	

24	64-QAM	0.607	3.643	2.637	13.187	18.2	17.8	
25	64-QAM	0.634	3.804	2.754	13.770	19	18.2	
26	64-QAM	0.679	4.072	2.948	14.739	20.6	19.4	
27	64-QAM	0.702	4.210	3.048	15.239	21.4	19.8	
28	256-QAM	0.549	4.394	3.181	15.904			
29	256-QAM	0.592	4.736	3.429	17.144			
30	256-QAM	0.618	4.943	3.579	17.893			
31	256-QAM	0.665	5.320	3.852	19.258			
32	256-QAM	0.692	5.537	4.008	20.041			
33	256-QAM	0.716	5.726	4.145	20.727			
34	256-QAM	0.827	6.618	4.791	23.956			

The link-level simulations presented in the IBC Paper [14] do not cover all configuration cases and all reception modes. Moreover, for Fixed reception, they correspond to the use of one antenna, while for portable / mobile reception two antennas are assumed, leading to diversity gain in the receivers. As such they provide an upper bound on the capacity associated to a given SINR value.

The values highlighted in green in the tables are the reference SINR values to use when translating a given SINR value for a given CP to the corresponding capacity, for 5 / 10 / 15 / 20 dB target SINR respectively. For example, § 1.6 shows that LPLT with reuse 1 offers the best coverage with a 100 µs CP, ensuring 20 dB in 100% of the target coverage area in suburban or 15 dB in urban area for Handheld Portable Outdoor reception.

Using the above tables, the indicative available capacity in a 5 MHz channel is 11.162 Mbit/s for suburban (MCS 22 in Table D2) and 7.792 Mbit/s for urban (MCS 18 in Table D2), if using two different 5 MHz channels, each having its own system characteristics. If the same carrier is to be used for both urban and suburban coverage, then the lowest MCS index must be selected to allow full coverage in both urban and suburban areas, hence limiting the capacity to 7.792 Mbit/s in both environments.

Annex E: Simulation of the Impact of practical antenna pattern

E1. Introduction

This Annex compares the effect on margin and coverage of using an antenna on LPLT, MPMT and HPHT sites that is subject to practical limitations rather than on ideal antenna characteristics. The range of antenna variation that exists means it is impractical to model all options, particularly in the case of LPLT, so a single example has been simulated to show its potential impact. For the LPLT case the antenna modelled is shown in Figure E6, for the HPHT and MPMT cases a typical 'omnidirectional' Broadcast antenna incorporating a 4 dB ripple was assessed.

E2. Generic case

The results on coverage of using practical antennas (realisable using existing infrastructure) rather than idealised antennas are shown in Figures E1 to E5. In all cases there is a reduction in coverage, however where there is an overlap in coverage and a surfeit of margin for a given SINR, there may be no real impact on coverage. Examples where coverage for a given SINR is maintained are LPLT suburban and LPLT urban where SINR is 20 dB or less, LPLT rural where SINR is 5 dB or less, MPMT and HPHT rural where the SINR is 10 dB or less.

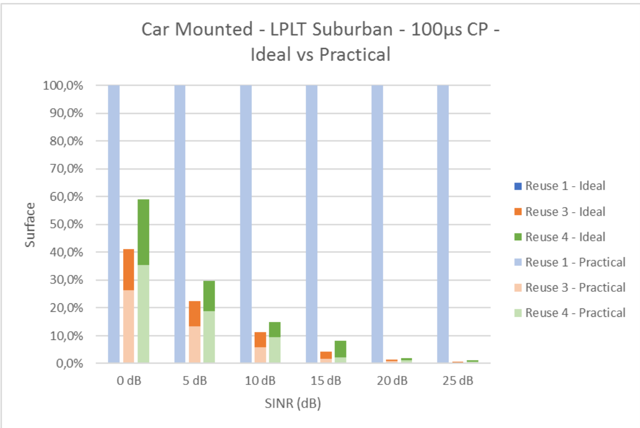


Figure E1

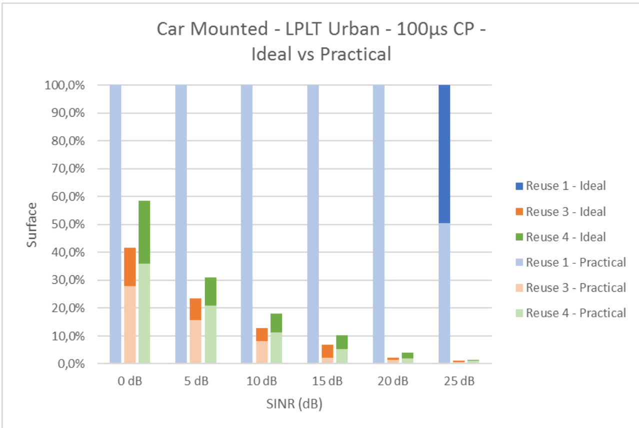
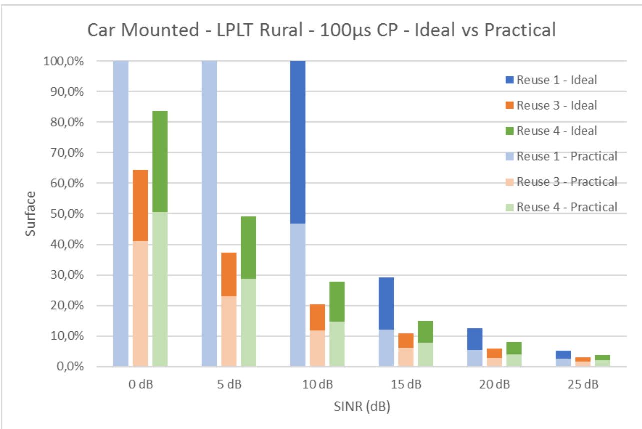


Figure E2



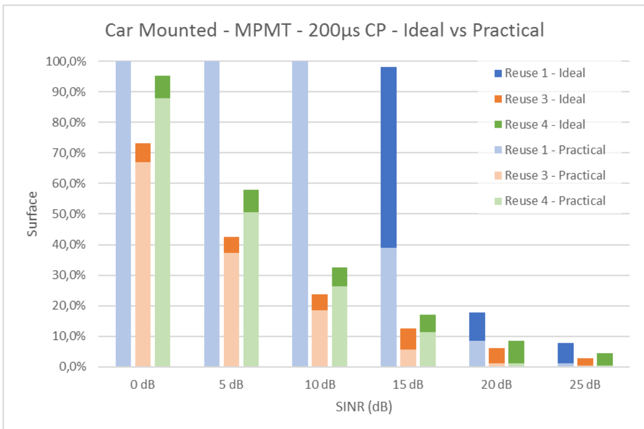


Figure E3 **Figure E4**

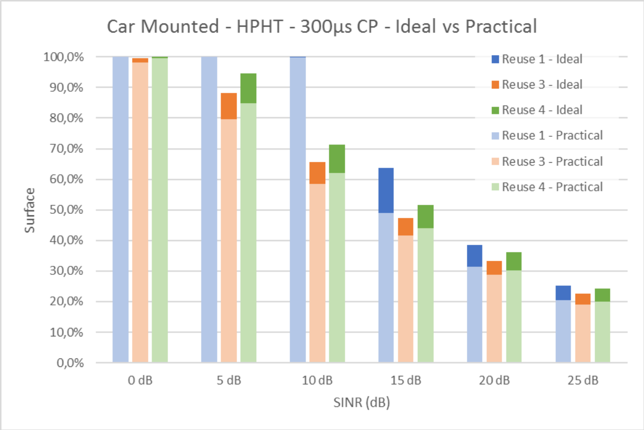


Figure E5

E3. ‘Real’ case

The coverage of an example 5G Broadcast network, based on an actual network, was simulated. The network consists of 130 LPLT sites operated as an SFN. It is designed to provide 95% population indoor coverage when using idealized antenna diagrams. The details of the modelled network are as follows:

- Extent of area: 30 km x 30 km, approximately 1000 km^2
- Environment: Dense Urban 20%, Urban 30% and Suburban 30%
- Type of reception: Handheld Indoor
- Number of sites: 130
- Antenna heights: 20 - 40 m
- Target population coverage: 95%
- EIRP of Sites 500 - 1000 W
- Total population within AOI about 7 million
- Total capacity of network About 10 Mbit/s

SFN system parameters were set in such a way that no SFN self-interference is present, symbol time is 800 µs and CP is 200 µs. Planning parameters were as specified in Annex A.

The antenna patterns used in the modelling are shown in Figure E6. The difference between the two idealized and distorted patterns are shown in red.

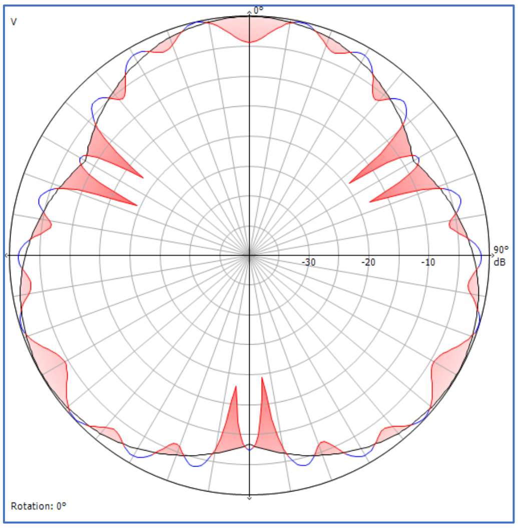


Figure E6: Modelled antenna patterns idealized and distorted

E4. Results

The original network using the 'idealized' antenna patterns provided the target 95% indoor population coverage. Repeating the coverage calculation using the practical antenna pattern provided 73% indoor population coverage. This indicates that the impact on coverage of a practical antenna pattern could be significant. It was estimated that about 30 additional sites would be needed to restore 95% population coverage. Alternatively, an increase of power of about 4 dB would be needed to restore coverage back to the original 95% population. Coverage plots for the two scenarios modelled are shown in Figures E7 & E8.

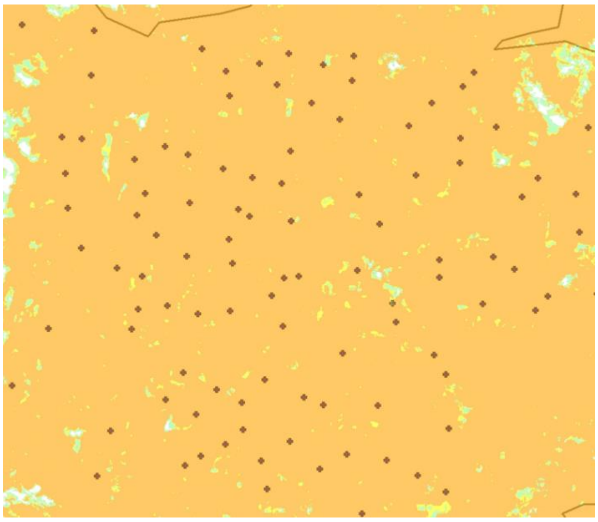


Figure E7: Idealized antenna 95% indoor population coverage

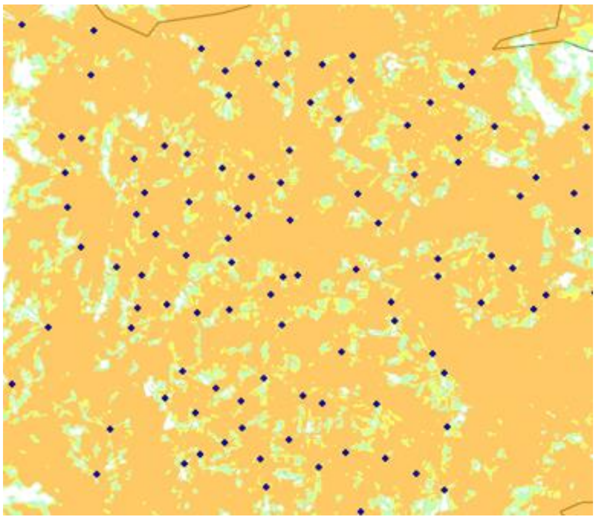


Figure E8: Practical antenna 73% indoor population coverage

The difference between the two predictions, i.e., the areas (red) where coverage is lost due to the change in antenna pattern is shown in Figure E9.

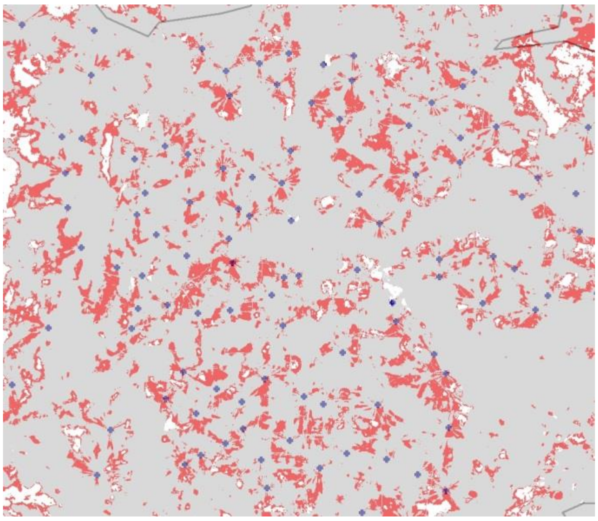


Figure E9: Difference plot

E5. Discussion

Broadcast antenna patterns, whilst not providing true omnidirectional coverage, are optimised to minimise nulls (ripple) in the patterns. Consequently, the impact on SINR at the edge of coverage of using practical patterns rather than 'idealised' omnidirectional patterns is small but not insignificant. For mobile antenna systems comprised of sector antennas, the impact, if not mitigated, could be significant at the edge of coverage. The impact on coverage could be reduced by increasing the EIRP, adopting an increased phase delay between sector antennas (cyclic delay diversity), a combination of the two or building a new antenna with a better pattern. Each has a cost implication that needs to be weighed against the potential loss in coverage.

E6. Conclusion

The sector antennas typically used by mobile systems are not designed to operate as arrays. If used for 5G Broadcast, such antennas would have deep nulls in the pattern, which may compromise coverage. Measures to mitigate this loss in coverage may be required. Existing broadcast antenna systems have already been optimised for coverage.