PERFORMANCE OF 5G BROADCAST AND BENEFITS OF PROPOSED TIME-INTERLEAVING ENHANCEMENTS

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ABSTRACT

In this paper, we assess the performance of the LTE-based 5G Terrestrial Broadcast system, popularly known as 5G Broadcast, for two realistic Single Frequency Networks: the UK's HPHT digital terrestrial TV (DTT) network and an example LPLT network with a 5 km inter-site distance (ISD) assembled from all the UK cellular networks appearing in Ofcom's Sitefinder. Using the UK Prediction Model (UKPM), we first calculate the network coverage for fixed rooftop, indoor, portable and mobile reception environments. The coverage results are then combined with physical layer simulations to calculate the expected system throughputs.

We provide tables of capacity for a wide set of modulation and coding schemes (MCS) and channel models that will be useful to the industry to map specific coverage predictions to throughputs provided by the 5G Broadcast physical layer radio interface.

Finally, we evaluate the performance improvements, considering both physical layer performance and system capacity, that the implementation of Hybrid Automatic Repeat reQuest (HARQ) based time-interleaving may provide. Our results verify the significant system capacity improvements of time-interleaving in realistic mobile scenarios that motivate its potential standardisation into the next releases of the 3GPP technical specifications.

INTRODUCTION

The 3rd Generation Partnership Project (3GPP) Release-16 specifies enhancements to the Long Term Evolution (LTE) evolved Multimedia Broadcast Multicast Service (eMBMS), popularly known as 5G Broadcast (1), to address the 5G requirements for dedicated broadcast networks, previously identified in 3GPP TR 38.913 (2):

- A 100 µs Cyclic Prefix (CP) for high mobility (i.e. 250 km/h) support in Low Power Low Tower (LPLT) Single Frequency Networks (SFN) networks, with inter-site distances (ISD) up to around 15 km;
- A 300 µs CP for the support of conventional SFN i.e. broadcast networks with High-Power High-Tower (HPHT) sites with ISD of 60 - 80km or more, targeting fixed rooftop reception; and

- A more robust Cell Acquisition Subframe (CAS) for reliable signal acquisition and synchronisation.

5G Broadcast allows SFN transmissions with 100% of the resources allocated to broadcast capacity and supports receive-only mode (ROM) devices, i.e. without uplink capabilities[1] (1). In this paper, we focus on the performance of the Physical Multicast Channel (PMCH) for dedicated broadcast carriers for the numerologies shown in Table 1, where T_{CP} is the duration of the CP (or guard interval), T_U the active symbol period, and T_{EI} the receiver's channel equalisation interval (EI) (3). The performance of the CAS is not addressed in this paper.

Subcarrier Spacing (kHz)	T_{CP} (μs)	T_U (μs)	T_{EI} (μs)	Comment
2.5	100	400	200	High mobility circa 250km/h, in LPLT networks with up to 15 km ISD.
1.25	200	800	267	CP specified in Release 14 for fixed rooftop reception support over LPLT network with up to 15 km ISD.
0.370	300	2700	900	Support for conventional SFN broadcast networks with 60 - 80 km ISD or more for fixed rooftop reception[2].

Table 1: 5G Broadcast numerologies investigated in this paper

As well as analysing the performance of the system on two realistic UK SFNs and providing tables of capacity of the 5G Broadcast physical layer radio interface, we evaluate the performance of a potential enhancement to the existing specification in the form of Hybrid Automatic Repeat reQuest (HARQ) based time-interleaving in terms of both link level and system capacity enhancements. We note that a comparison of the performance of 5G Broadcast against other existing broadcasting technologies is not in the scope of this paper and is therefore left for future work.

TRANSMISSION NETWORKS AND RECEIVING ENVIRONMENTS

Transmission Networks

The two transmission networks (configured as a national SFN) are as follows:

- *The UK DTT network*: 1,163 sites with locations, antenna heights, effective radiated powers (ERP) and antenna patterns etc that are in use today.
- *A UK cellular-type network*: 7,592 macro sites selected from across all seven of the LPLT networks in Ofcom's SiteFinder database to produce a target ISD[3] of 5 km.

All LPLT network transmitters have been assigned an Effective Isotropic Radiated Power (EiRP) of 30 dBW and a tri-sector antenna pattern based on Table A.1-1: 3GPP Case 1 and 3 (Macro-cell) (4).

[1] A receive-only-mode device could be integrated into a user equipment device (e.g. smartphone) with uplink capabilities to concurrently consume both broadcast and unicast data transmissions on separate carriers.

[2] This numerology has two Reference Signal (RS) patterns specified, both with same T_{EI}. In this paper we consider RS type1 which has a time separation between RS on the same subcarrier of 4 OFDM symbols.

[3] Although ample cellular sites exist in cities that enable an ISD of 5km, in rural areas where there are fewer sites, the ISD is often greater (5).

Receiving Environments

Four different receiving environments have been considered:

- *Fixed Rooftop*: stationary receivers connected via co-axial cable to high gain external rooftop antennas at 10m above ground level (agl).
- *Portable Handheld Indoor or Outdoor*: Indoor or outdoor reception at 1.5m agl on portable devices with integrated antennas e.g. smartphones and tablets.
- *Car mounted*: in-vehicle receivers connected to a well-designed antenna system integrated into the vehicle (two antennas are assumed at 1.5m agl) (6).

Link Budgets

Link budgets, particularly from the receiving antenna to the receiver terminals, indicate the coverage that might be possible in one receiving environment relative to another. Figure 1 illustrates the main components of the link budgets for our four receiving environments while Table 2 summarises their effect. The link budget parameters shown in Table 1, and used in the ensuing coverage simulations, may be found in (6) & (7) .

As an example, a given field strength at 10 m above ground level will result in a signal power at the receiver terminals of an indoor handheld UE some 46 dB lower than the terminals of a receiver connected by a low loss cable to an external rooftop aerial. This very significant reduction in received power indicates that we should find the coverage area for portable devices to be much smaller than for devices connected to rooftop antennas in networks designed for rooftop reception.

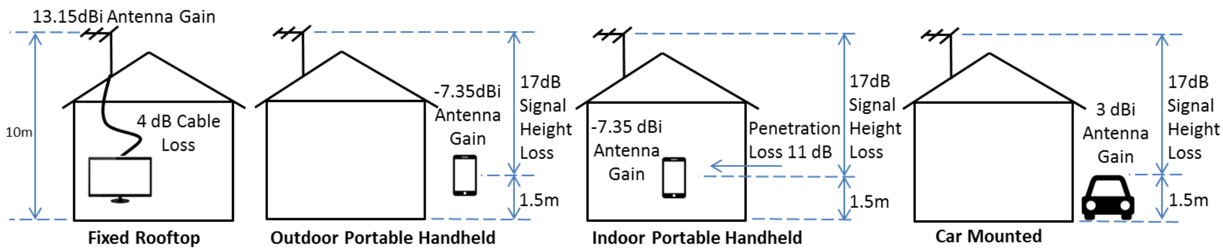

Figure 1: Receiving environments.

System Aspect	Fixed Rooftop	Car Mounted	Outdoor Portable Handheld	Indoor Portable Handheld
Receiving Antenna Gain	13.15 dBi	3 dBi	-7.35 dBi	-7.35 dBi
Hand Loss	0 dB	0dB	2 dB	2 dB
Cable Loss	4 dB	0 dB	0 dB	0 dB
Height Loss (10m vs 1.5m)	0 dB	17 dB	17 dB	17 dB
Outdoor to Indoor Penetration Loss	0 dB	0 dB	0 dB	11 dB
Link Budget Difference	Reference	**23.15 dB**	**35.5 dB**	**46.5 dB**

Table 2: Link budgets

Link budgets play a crucial role in determining the extent of coverage/capacity, and there can be some variation in the values used in different studies. For example, (8) & (9) indicate that height losses lower than those in (7) may be more appropriate. Further work to determine the most appropriate values for the elements in the link budgets is greatly encouraged.

PERFORMANCE OF THE 5G BROADCAST PHYSICAL LAYER RADIO INTERFACE

Transmission, Channel Models and Receiver Assumptions

The performance of the 5G Broadcast physical layer radio interface has been evaluated with a simulation platform developed as per the 3GPP technical specifications TS36.211 (Physical Channels and Modulation) (10), TS36.212 (Multiplexing and Channel Coding) (11) and TS36.213 (Physical Layer Procedures) (12).

We use the Tapped Delay Line (TDL) 5G channel models defined in (13). Following the evaluation methodology used in the 3GPP Study Item of LTE-based 5G Terrestrial Broadcast (6), TDL-E is used for the rooftop reception environment with Line of Sight (LOS), whilst TDL-A is used for the other handheld/mobile reception environments with Non-Line of Sight (NLOS). In this paper, we use the root mean square Delay Spread (DS) derived from system level simulations in (14) that characterise SFN propagation for the transmission and reception environments defined (6).

The receiver uses one or two antennas with uncorrelated fading with a Maximum Likelihood demapper and the algorithm used for the turbo decoder is a max-log-MAP decoding with a maximum of eight iterations. The simulations were carried out using realistic channel estimation. This comprises linear temporal interpolation between Reference Symbols (RSs) located on the same subcarrier, followed by MMSE frequency interpolation. The coefficients are chosen so as to minimise the expected squared error between the estimate and the actual response, taking into account the noise on the RSs and assuming a power delay profile that has equal power at all delays within a defined EI and zero elsewhere. The EI duration is a design parameter and for the simulations in this paper it was set to 90% of the Nyquist limit (15). The centre of the EI is aligned with the centre of the CP[4] so as to provide equal tolerance of echoes before the beginning or after the end of the CP. The linear temporal interpolation is a basic approach and it is likely that real receivers could do better. However, a more sophisticated temporal interpolator requires more memory to store the RSs and data-bearing Resource Elements (RE) from more symbols. Conversely, the MMSE frequency interpolator simulated here has greater complexity than is likely for a real receiver implementation.

HARQ-based Time-Interleaving

In (16), it was first shown that the introduction of time-interleaving in the LTE physical layer provides significant performance gains for the PMCH channel in mobile environments. The solution proposed in (16) was based on a row-column interleaver structure of the type specified in DVB-T2, where the REs from multiple subframes are written column-wise into the interleaving memory and read out row-wise to spread the transmitted information from multiple Transport Blocks (TBs) uniformly across time. However, the implementation of time-interleaving as proposed in (16) may require substantially more in-chipset memory to achieve sufficient interleaving depths. (17) proposed to reuse Hybrid Automatic Repeat reQuest (HARQ) processing, which is already used in unicast to request retransmission (or

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[4] Strictly, the EI is an interval in the *delay* domain, whilst the CP is a portion of each OFDM symbol in the *time* domain. What is meant here is that the EI is positioned such that a path falling in the middle of the EI also falls in the middle of the range of delays for which there is no inter-symbol or inter-carrier interference (ISI or ICI). Since this delay range is equal in extent to the CP duration, it is a common shorthand to refer to it as “the CP”.

incremental redundancy) upon a TB decoding failure, to spread the TB information of the PMCH channel across multiple subframes and therefore exploit time diversity. Furthermore, the HARQ chip memory currently remains unused for dedicated MBMS carriers (i.e. with no unicast transmissions) and can be repurposed to perform PMCH time-interleaving, i.e. no additional in-chip memory may be required. The performance benefits of HARQ-based time-interleaving in (17) were confirmed in (18) and compared against a block-based time-interleaving as proposed in (16).

The operation of HARQ-based time-interleaving is shown in Figure 2. The size of each of the *m* parallel TBs input to the physical layer is scaled up by *n*, the number of redundancy versions (RV), and rounded to the closest valid TB Size (TBS) in (12). Each RV of the original TB is mapped to one subframe across time to achieve an interleaving depth of $m(n\text{-}1)+1$ subframes. The proposal in (17) was applied only to the numerology with CP 100 µs but it should also be directly applicable to the other numerologies with similar time diversity performance benefits.

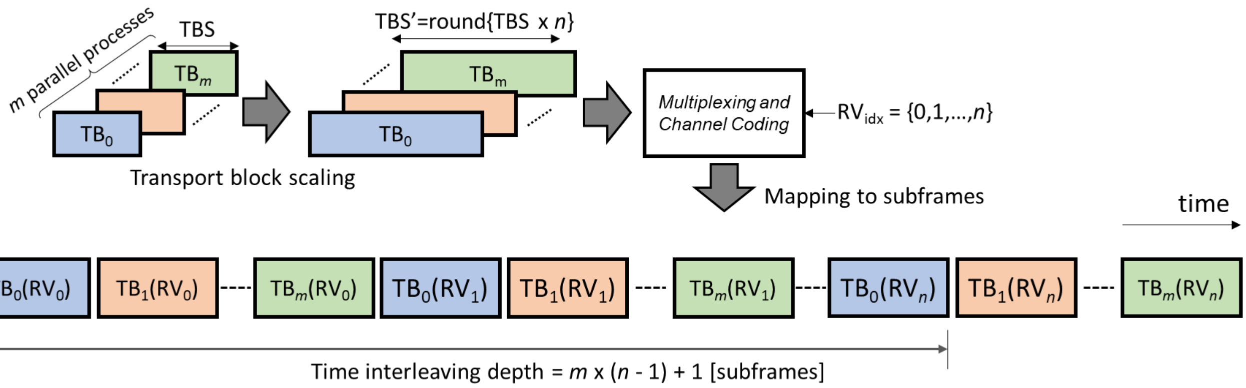

Figure 2: HARQ-based time-interleaving for 5G Broadcast with *n* RVs and *m* parallel processes.

Capacity of 5G Terrestrial Broadcast

In this section, we provide numerical evaluations of 5G Broadcast link-level capacity results for the PMCH channel for the three numerologies considered in this paper in representative channel models of SFN operation within a 10 MHz channel bandwidth. In Tables 3 & 4 (below) the columns Qm, CR and SNR show the modulation order, effective code-rate and required SNR (dB) to achieve a Transport Block Error Rate (BLER) of 0.1%. To achieve such SNR targets, simulations are run until at least 20 TBs in error are detected or a maximum of 25000 TBs are simulated. The reported throughputs are those provided by the physical layer to upper layers and include loss due to the periodic transmission of the CAS. The speeds reported in the tables associated with the Doppler spread in Hz are calculated for a carrier frequency of 700MHz. The channel models used for the evaluations with100 µs and 200 µs CPs have delay spreads representing LPLT network with 15 km ISD, and the evaluations with 300 µs CP have delay spreads representing a HPHT network with 125 km ISD. More detail information about these network parameters can be found in (6). The MCS settings selected for the Tables 3 & 4 (with effective code-rate of at least 1/3) with the performance of 100 µs CP and 200 µs CP are based on table 7.1.7.1-1 of (12) and the MCS settings (with effective code-rate of at least 1/3) for Table 4 with the performance of 300us CP are based on table 11.1-1 of (12); neither include 256QAM.

Table 3: 5G Broadcast PMCH capacity with 2.5 kHz subcarrier spacing, 100 µs CP duration, 10 MHz channel bandwidth, TDL-A channel model (mobile/handheld) with 20 µs Delay Spread with two-antenna receivers. Values with ND stand for Non-decodable.

		Rel-16 without time-interleaving				Rel-16 with HARQ-based time-interleaving (*n*=8, *m*=16)		
		CR	Throughput (Mbps)	SNR (dB)		CR	Throughput (Mbps)	SNR (dB)
MCS	Qm			3 km/h (2Hz)	160 km/h (104 Hz)			160 km/h (104 Hz)
4	2	0.34	3.5	3.6	3.8	0.34	3.6	1.5
5	2	0.41	4.3	4.6	4.6	0.41	4.3	2.7
6	2	0.48	5.0	5.6	5.8	0.47	4.9	3.4
7	2	0.58	6.0	7	7.2	0.57	6.0	4.7
8	2	0.65	6.8	7.8	8.2	0.64	6.7	5.8
9	2	0.75	7.8	9.2	9.6	0.74	7.8	7.4
10	4	0.37	7.8	8.2	8.6	0.37	7.8	6.2
11	4	0.41	8.5	9	9.4	0.41	8.7	7
12	4	0.46	9.7	10	10.4	0.46	9.6	7.7
13	4	0.53	11.2	11.2	11.4	0.53	11.1	9.1
14	4	0.60	12.6	12.4	12.8	0.59	12.4	10.1
15	4	0.66	13.8	13.2	13.8	0.67	14.0	11.5
16	4	0.71	14.9	14.2	14.8	0.70	14.6	12.1
17	6	0.47	14.9	14.4	15	0.46	14.6	12.2
18	6	0.51	16.0	15	15.6	0.52	16.2	13.4
19	6	0.57	17.9	16.4	17	0.57	17.9	14.6
20	6	0.62	19.4	17.4	18.6	0.61	19.2	15.7
21	6	0.66	20.8	18.4	19.8	0.66	20.7	16.8
22	6	0.71	22.3	19.6	21.2	0.70	22.1	18.2
23	6	0.79	24.8	21.6	25	0.79	24.8	ND
24	6	0.85	26.7	26.4	ND			
25	6	0.88	27.6	28	ND			
26	6	0.95	29.8	ND	ND			
27	6	0.98	30.9	ND	ND			

Table 4: 5G Broadcast PMCH capacity with 1.25 kHz subcarrier spacing (200 µs CP) and 0.370 kHz subcarrier spacing (300 µs CP) in 10 MHz channel bandwidth. TDL-A and TDL-E channel models represent mobile/handheld and rooftop reception conditions, respectively. Values with ND stand for Non-decodable.

	1.25 kHz SCS, CP 200 µs						**0.370kHz SCS, CP 300 µs**				
				SNR (dB)						**SNR (dB)**	
MCS	**Qm**	**CR**	**Throughput (Mbps)**	**TDL-E 16µs (1 Hz) 1-Rx**	**TDL-A 20µs 3 km/h (2 Hz) 2-Rx**	**TDL-A 20µs 160 km/h (104 Hz) 2-Rx**	**Qm**	**CR**	**Throughput (Mbps)**	**TDL-E 45µs (1 Hz) 1-Rx**	**TDL-A 50µs 3 km/h (2 Hz) 2-Rx**
5	2	0.37	4.3	4	4	4.6					
6	2	0.43	5.0	4.8	5	5.6	2	0.34	5.0	3.6	4
7	2	0.52	6.0	6	6.2	6.8	2	0.41	6.0	4.6	4.8
8	2	0.59	6.8	6.8	7	7.8	2	0.47	6.7	5.2	5.6
9	2	0.67	7.8	8	8.2	9	2	0.53	7.7	6	6.4
10	4	0.34	7.8	7.8	7.8	8.4	2	0.60	8.6	6.8	7.2
11	4	0.37	8.5	8.4	8.4	9.2					
12	4	0.42	9.7	9.2	9.2	10.2					
13	4	0.48	11.2	10.4	10.4	11.4	4	0.38	11.1	8.6	8.8
14	4	0.54	12.6	11.6	11.4	13	4	0.44	12.8	9.8	9.8
15	4	0.59	13.8	12.4	12.4	14	4	0.48	13.8	10.2	10.6
16	4	0.64	14.9	13.2	13	15.2	4	0.51	14.7	10.8	11
17	6	0.43	14.9	13.8	13.4	15.8	4	0.55	15.9	11.6	11.8
18	6	0.46	16.0	14.4	14.4	17	4	0.62	17.9	12.8	13
19	6	0.51	17.9	15.6	15.4	19.6	4	0.67	19.3	13.6	13.6
20	6	0.55	19.4	16.8	16.4	22.8	4	0.72	20.7	14.6	14.8
21	6	0.60	20.8	17.8	17.2	ND	6	0.48	20.7	15	14.8
22	6	0.64	22.3	19.4	18.2	ND	6	0.52	22.4	15.8	15.6
23	6	0.71	24.8	22.8	21.8	ND	6	0.57	24.8	17.2	16.8
24	6	0.76	26.7	ND	ND	ND	6	0.61	26.4	18.2	17.8
25	6	0.79	27.6	ND	ND	ND	6	0.64	27.5	19	18.2
26	6	0.85	29.8	ND	ND	ND	6	0.68	29.5	20.6	19.4
27	6	0.89	30.9	ND	ND	ND	6	0.70	30.5	21.4	19.8

Doppler Performance and the Impact of Time Interleaving

Figure 3 presents the Doppler tolerance for the three considered numerologies of 5G Broadcast in a TDL-A channel model with 20 µs DS and two-antenna receivers at a carrier frequency of 700 MHz. The results show that although the 200 µs CP numerology with 1.25 kHz SCS has lower Doppler tolerance than the 100 µs CP with 2.5 kHz SCS, the performance at 160 km/h is similar for both numerologies. The results also show that the 300 µs CP numerology with 0.370 kHz SCS is not well suited for high speed mobile reception where at 60 km/h the service was not decodable.

The introduction of HARQ-based time interleaving with an interleaving depth of 241 ms (19) can increase the capacity by 28% at intermediate and high speeds (30 km/h to 250 km/h). At lower speeds, where deep fades can last longer it can eventually exceed the time interleaving depth, thus reducing the performance improvements it provides.

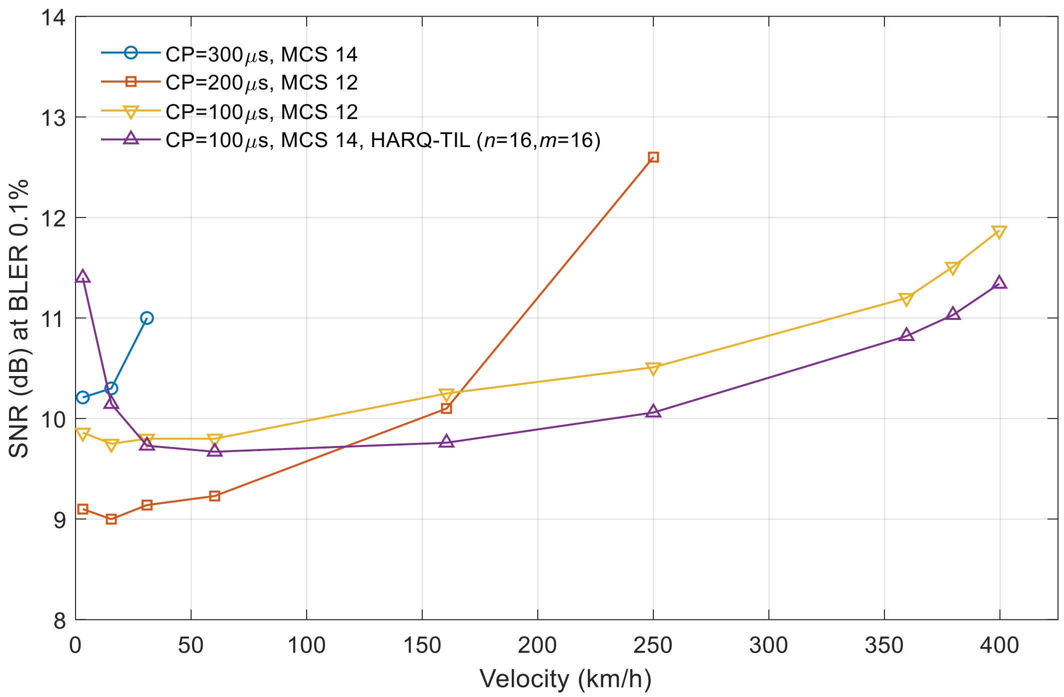

Figure 3: SNR (dB) at BLER 0.1% vs. velocity (km/h) for 5G Broadcast numerologies with 100 µs, 200 µs and 300 µs CP. HARQ-based time-interleaving with 241 ms interleaving depth.

COVERAGE RESULTS

The coverage simulations are based on the BBC's implementation of the UKPM, which is yet to be fully calibrated for reception at 1.5m above ground level in the UHF band. The coverage analyses at this height, particularly for the LPLT network, should therefore be viewed as a first step in understanding the potential of 5G Broadcast for the distribution of audio/visual content in realistic networks. Further work and more detailed analyses are therefore encouraged.

The simulations use conventional broadcast methodologies, in line with (7), unless otherwise stated. Table 5 sets out some key simulation parameters for convenience. Regionality and Interference from non-UK stations has not been considered.

Parameter	Description
Prediction Resolution (pixel size)	100m
Location Variability (at receiving pixel)	5.5dB
Wanted/Interfering Signal Summation	Schwartz & Yeh
Receiving antenna alignment	Station providing highest SINR
Frequency (MHz)	702
Wanted/Interfering time percentage	50/1
Effective length of EI	90% (15)
Channel/Occupied Bandwidth	10/9 MHz

Table 5: Coverage simulation parameters

UKPM and Simulation Parameters

The proportion of households (HH) and roads (motorways and A roads) covered was found for each pixel by applying the coverage thresholds and corresponding counting method in Table 6. For the cut-off counting method, all HH, or the entire road length within the pixel is considered covered should the locational coverage probability (P_L) of the pixel meet the coverage threshold. For indoor coverage both the proportional and cut-off counts have been used, depending on the value of P_L. The product of P_L and the number of HH in the pixel is used for P_L in the range 80 to 95% – the proportional count. Above 95%, all households in the pixel are considered covered – the cut-off count. The proportional count is intended to reflect the ability of the user to position the receiver in a location with favourable reception, particularly for the case of audio where a device may be positioned near a window. In all cases, if a pixel's coverage does not meet the relevant threshold, the pixel is deemed to be entirely deficient, with no households or length of road covered.

Reception Environment	Coverage Threshold	Counting Method
Fixed Rooftop	≥70% locations	Cut-off
Outdoor Portable Handheld	≥95% locations	Cut-off
Indoor Portable Handheld	≥80<95% locations ≥95% locations	Proportional Cut-off
Car Mounted	≥99% locations	Cut-off

Table 6: Counting methods for coverage simulations

DTT Network (HPHT)

Figure 4 shows the coverage that might be achievable with the HPHT DTT network. The following observations have been made:

- The 300 µs CP appears to be sufficiently long to provide near-universal coverage in national SFN at 20dB SINR for fixed rooftop reception.
- The HPHT DTT network does not appear to be well dimensioned for the provision of near-universal coverage to handheld or mobile devices, particularly indoors.

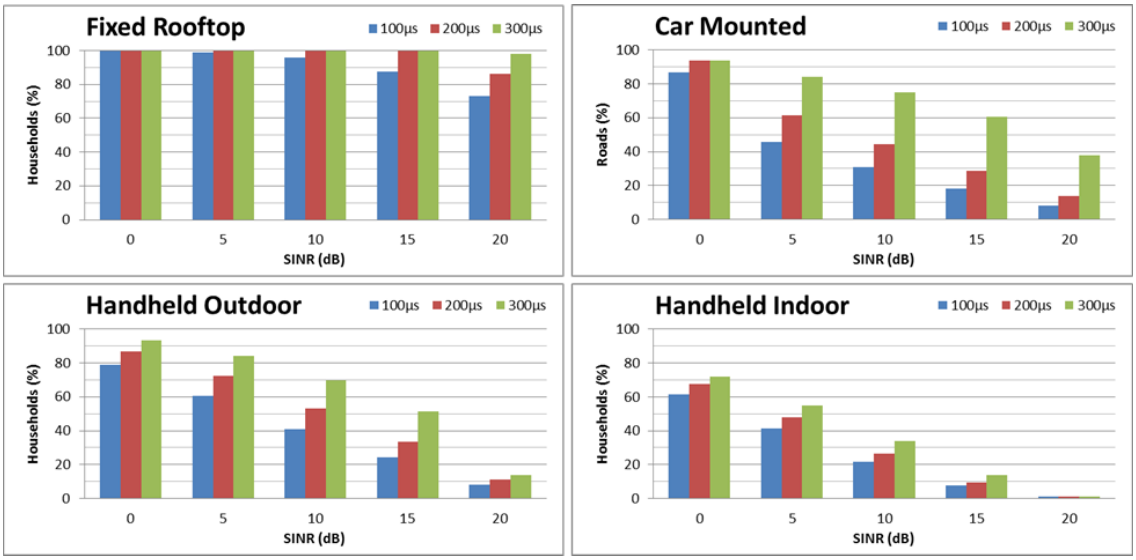

Figure 4: Coverage predictions in HPHT DTT network in the considered reception environments.

Cellular Network (LPLT)

Figure 5 shows the coverage and capacity that might be achievable with the LPLT cellular network. The following observations have been made:

- Near universal coverage for fixed rooftop reception appears achievable with any of the three CPs with an SINR of 20 dB or more
- An SINR in the order of 10 dB may provide near universal coverage of roads and households for car mounted and handheld outdoor devices respectively, with 'usefully expansive' indoor coverage of around 60% of households.
- The 200 µs CP would appear to provide a marginally higher coverage than the 100 µs CP and appears to be the most versatile, general purpose numerology for LPLT unless very high-speed reception is required.

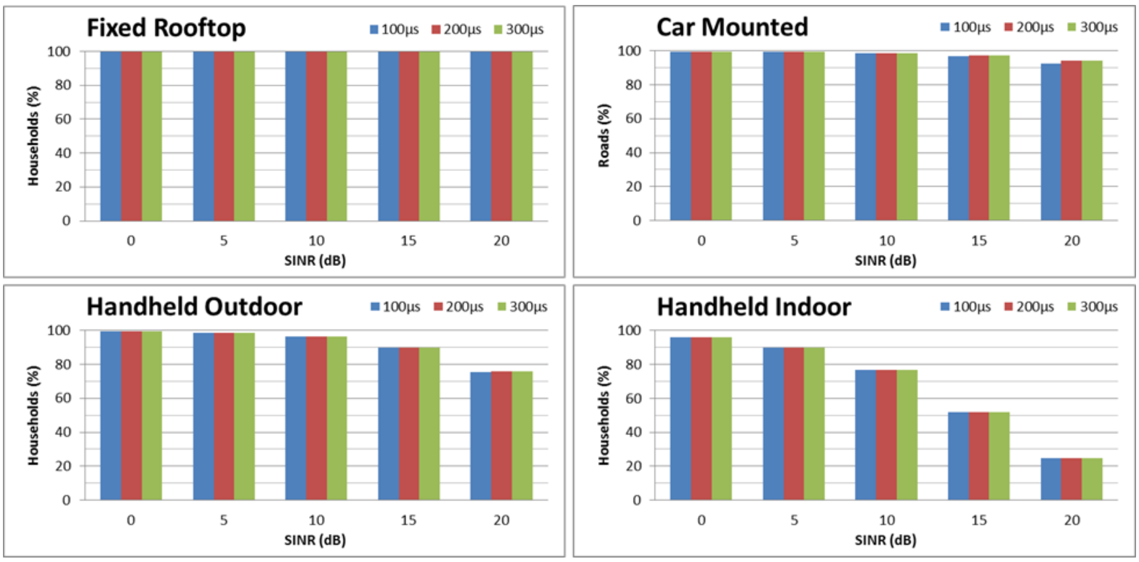

Figure 5: Coverage predictions in LPLT network in the considered reception environments.

SYSTEM AND NETWORK CAPACITY RESULTS

Combining the link and system level simulations, the following examples are illustrative of the performance of 5G Broadcast in the two networks considered with a 10 MHz channel:

HPHT

- The 300 µs CP is sufficiently long to provide near universal coverage (e.g. 98% of households) to fixed rooftop antennas in national SFN at high SINR (e.g. 20 dB). MCS 25 may provide 27.5 Mbps. The 200 µs CP is insufficient at high SINR.
- MCS 25 with 300 µs CP may, however, cover fewer than 20% outdoor handheld devices and even fewer devices indoors. Furthermore, the narrow subcarrier spacing, and sparse reference symbols of the considered mode, would be unsuitable for high speed reception in vehicles.
- MCS 7 with 300 µs CP could provide 6 Mbps to around 80% and 70% of outdoor and indoor handheld devices respectively (5 dB SINR).

LPLT

- The 100 µs and 200 µs CP provide similar performance for handheld devices in the nominal 5 km ISD LPLT network. Both CPs are sufficiently long to reduce SFN self-interference and have similar Doppler performance up to 160 km/h. For higher speeds, 100 µs CP is superior.
- For both CPs, MCS 12 could provide 9.7 Mbps to around 95% of households/roads for handheld outdoor and car mounted reception; indoor coverage is possible to around 75% of households.
- HARQ-based time-interleaving would improve the coverage/capacity in car-mounted environments. For example, the capacity of MCS 12 (9.7 Mbps) could increase by 28% for speeds between 30 km/h to 250 km/h.
- It would also be possible to provide high bitrate, near universal coverage for fixed rooftop reception using LPLT networks.

CONCLUSIONS

In this paper we have assessed the performance of the 5G Broadcast system for two realistic networks in the UK, the HPHT DTT network and a LPLT network with a 5 km ISD, in various reception environments: handheld outdoor, handheld indoor, car mounted and fixed rooftop reception. Our coverage and physical layer capacity predictions show that it may be possible to provide a high throughput to fixed rooftop receivers with near universal coverage from the considered HPHT DTT network with the modes specified in 5G Broadcast. However, the provision of mobile services from HPHT is more challenging leading to either significantly reduced coverage or to a low spectrally efficient transmission. On the other hand, a denser LPLT network could provide higher throughputs in mobile environments with spectral efficiencies close to 1 bit/s/Hz at high coverage values and high-speed reception. We have also shown the significant performance benefits by the implementation of HARQ-based time interleaving that motivates its standardisation into future releases of LTE-based broadcast or into a potential evolution of the next generation wireless access technology 5G NR broadcast.

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