Time and Frequency Interleaving for broadcast services in 3GPP Systems

Time and Frequency Interleaving (TFI) is a key feature for robust broadcast transmissions in time-frequency varying environments, in particular for mobile reception. TFI was considered and evaluated by multiple companies during the 3GPP Rel-16 standardisation of LTE-based 5G Broadcast with significant support from companies. Furthermore, time interleaving has also been proposed for NR Multicast and Broadcast Services (NR MBS) in 3GPP Rel-17. Multiple papers have been published on the performance of TFI for LTE-based 5G Broadcast (see Section 6). In summary, a significant number of papers and work from different sources is available showing the performance benefits of TFI and hence, the consensus view within 5G-MAG is that addressing the topic in 3GPP specifications would be valuable to increase the robustness of the broadcast services specified by 3GPP.

To support the specification development in 3GPP, 5G-MAG has produced this Report summarising key results and potential specification impact to introduce Time-Frequency Interleaving for broadcast services in 5G systems.

Contents

1. Time and Frequency Interleaving in state-of-the-art broadcast technologies

Time and frequency interleavers are crucial components of wireless broadcast standards [1] to increase the robustness of the transmissions. Due to the relatively wide range of link quality operating points that can be experienced by different User Equipment (UEs) for a range of Low-Power Low-Tower (LPLT), High-Power High-Tower (HPHT), Medium-Power Medium-Tower (MPMT) and hybrid network settings in practice, interleavers have been widely studied and adopted as they are used jointly to capture time and frequency diversity. This is necessary to overcome the performance loss due to the lack of a feedback link in conjunction with Hybrid Automatic Repeat reQuest (HARQ) retransmissions in broadcast systems.

Time and frequency interleavers have been widely adopted in different wireless broadcast standards. For example, in DVB-T2, FEC-encoded codewords corresponding to data payload belonging to the same TV service are grouped at the physical layer, and they are time interleaved before being transmitted [1]. This interleaver relies on a fixed time interleaving memory buffer, with interleaving depths depending on the peak data rate of a given service, so that the lower the data rate, the larger the time interleaving depth. For example, this translates to an interleaving depth of up to 350 ms for a 3 Mbps service delivered using a QPSK constellation with 1/2 code rate, while for higher data rates, such as 256-QAM with 2/3 code rate, the interleaving depth can be up to around 70-80 ms [1].

Another widely known broadcast standard that actively adopts time and frequency interleavers is ATSC 3.0 [2]. It provides two different optional types of time interleavers, namely a Convolutional Time Interleaver (CTI), and a Hybrid Time Interleaver, which operate on either an intra-subframe level, or/and inter-subframe level. Regarding the interleaving depth, ATSC 3.0 interleavers can provide up to 400 ms when configured for intra-subframe interleaving in certain transmission modes, and larger depths in inter-subframe interleaving for low bit rate streams [2]. Furthermore, ATSC 3.0 includes several options for frequency interleavers depending on the FFT modulation size, which operate on the tones[1] of each OFDM symbol separately, and the tone interleaving indexes are alternated depending on which OFDM symbol within a subframe the interleaver operates on.

[1] Tones or individual sub-carriers in each symbol in time of an OFDM modulation

2. Time and Frequency Interleaving for 3GPP systems

2.1. Introduction

Despite the constraints of hardware reuse, it is possible to design additional broadcast-specific features on top of the broadcast services already specified by 3GPP. One of the key aspects in designing these enhancements is to identify the building blocks in the cellular modem that can be reused with minimal modifications, to enable these new features, without the need of additional hardware. As an example, the design of a time interleaver by reusing the "HARQ combining" building block, present in all cellular modems, is detailed below.

Harnessing time diversity for LTE-based 5G Terrestrial Broadcast was first proposed to 3GPP in[3], where it was pointed out that physical-layer time interleaving provides performance benefits, especially for high-mobility use cases. However, the solution in [3] would require anywhere between a 13x to 39x increase in the Log-likelihood Ratio (LLR) buffer memory of the receiver. Indeed, in [3], it was proposed to only apply such a solution for small values of system bandwidth. It may be noted that a portion of the HARQ buffer memory may be utilized for dedicated broadcast reception, that may otherwise have been utilized by unicast, if dedicated broadcast reception was not enabled.
The other source of diversity that can be leveraged to further enhance link-level communication performance is frequency diversity. Frequency interleavers, such as the one proposed in ATSC 3.0 [2], typically operate on an OFDM symbol-by-symbol basis and aim at spreading channel fades in the frequency domain so that codeblocks experience spectral diversity. This is important in broadcasting use cases or standards to mitigate the fading effects resulting from channels having significant frequency selectivity, owing to large delay spreads.

2.2. HARQ-based time interleaving and cellular modem-friendliness

Reference [4] outlines a design that provides time-diversity without increasing the LLR buffer memory at the receiver. The key to the approach is the reuse of the building block behind HARQ retransmissions and combining, which allows to spread the coded bits of a transport block (TB) across multiple non-consecutive subframes. For throughput parity with non-interleaved transmission, the TB size is scaled by n—the number of redundancy versions (RVs) used for each TB. With this approach, one can use the "HARQ memory" to store the LLRs corresponding to each RV and decode after all n RVs for a TB have been received. In Figure 2.2-1, this mechanism is depicted: each RV will span a single slot/subframe, and each TB will be transmitted over n occasions, with a separation of m slots between each transmission.

The following two key techniques, present in the current HARQ retransmission framework, are used to build the time interleaver

(1) At a given transmission time interval (TTI), the modem is only required to process reception from a single TB. The ordering of the coded bits within one TTI is the same as that in current cellular systems.
(2) The already existing "HARQ-process handling" framework is re-used.

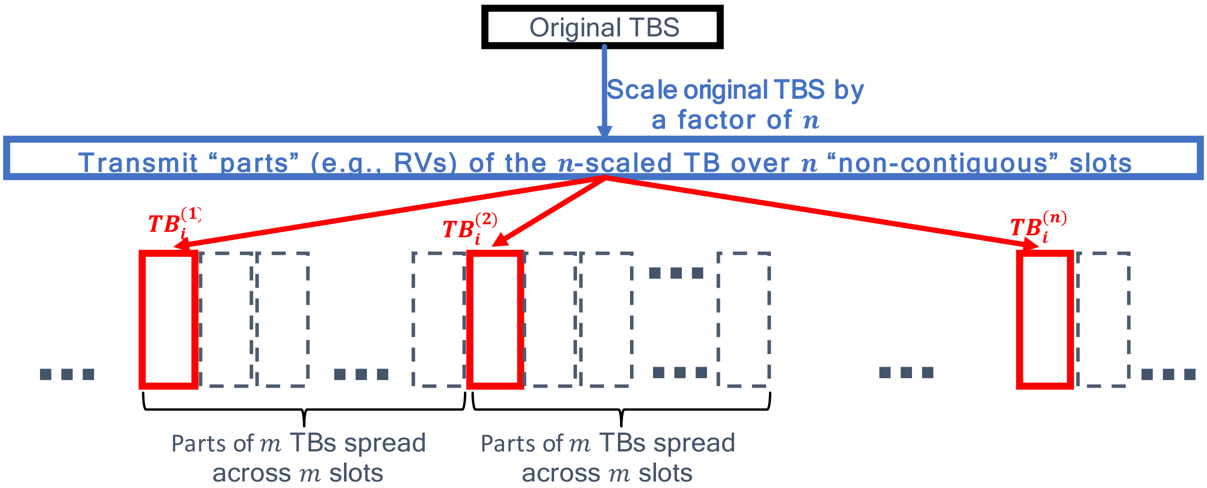

Figure 2.2-1: Interleaved transmission of "HARQ redundancy versions" of (scaled) transport blocks across slots/subframes.

As described next in Section 2.3, there are further nuances—notably, the generation of "modified redundancy versions"—that are integral to this design, but which can also be easily facilitated within the purview of the current cellular modem architecture.

Also, due to a large (scaled by n) TB size to facilitate the time interleaving described above, the number of codeblocks in a TB increases approximately by a factor of n. This may cause codeblock localization in frequency, as described in [4] and [5]. As a result, a tone-level frequency interleaver is incorporated to spread out the codeblocks in frequency as detailed in Section 2.4.

2.3. Details of Time Interleaving

There are two main drawbacks of reusing the *legacy* RV definitions:

1) For most cases, using the legacy RVs would not allow for transmitting a large portion of the systematic bits, since the coding rate for the initial few slots/subframes may be greater than one.
2) There are only 4 redundancy versions defined, which would limit the interleaving depth to $n \leq 4$ slots/subframes.

To overcome the above drawbacks, the proposed design of "*modified*" RVs in Figure 2.3.-1 ensures that the coded bits for RV_i start right after those for RV_{i-1} (cf. Section 2.3.1), and the restriction to 4 RVs is removed (cf. Section 2.3.2).

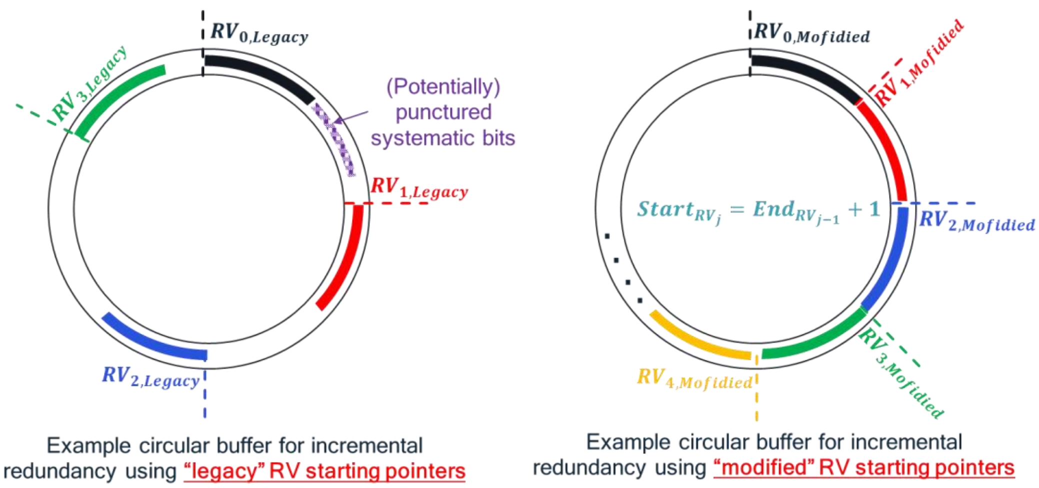

Figure 2.3-1: Illustration of "legacy" vs "continuous" RVs.

2.3.1. Generating "continuous" redundancy versions of a TB

Due to the scaled Transport Block Size (TBS), the legacy RV definitions may not be optimal for the proposed time interleaving solution since the systematic bits may potentially be punctured. To overcome this situation a modified RV definitions as illustrated in Figure 2.3-1 is proposed, such that the systematic bits are not punctured. More details can be found in [4].

2.3.2. Ordering of redundancy versions

To spread out the systematic bits of each codeblock (carried by the lower-indexed RVs) within the TB as far apart in time as possible, the sequence $\{RV_0, RV_2, RV_3, RV_1\}$ for $n = 4$ is used, while the sequence $\{RV_0, RV_4, RV_6, RV_2, RV_7, RV_3, RV_5, RV_1\}$ for $n = 8$ is used [4].

2.4. Details of Frequency Interleaving:

2.4.1. Overview: Frequency interleaving across codeblocks

As discussed before, with the scaled TB sizes, the number of codeblocks in a TB increases, thereby requiring frequency interleaving of the OFDM symbols. The main principles behind this proposed frequency interleaver are:

1) The tones corresponding to the codeblocks are written row-wise.
2) Pseudo-random shifts are applied to the columns. This prevents periodic fades in the frequency domain (e.g., from two strong taps spaced apart in the delay domain) from affecting specific codeblocks negatively.
3) Elements are read column-wise.

Assuming the modulation symbol vector y prior to frequency interleaving has N_{sc}^{DL} components, i.e., $\boldsymbol{y} = [y[0], y[1], \dots, y[N_{sc}^{DL} - 1]]$, the tone-level interleaving operation is performed as indicated in [4] and described as follows (following the principles of subclause 5.1.4.1.1 of TS 36.212)[2]:

1) Group the modulation symbols into sub-blocks of M tones each to obtain a vector $\boldsymbol{z} = \left[\boldsymbol{z}(\boldsymbol{0}), \boldsymbol{z}(\boldsymbol{1}), \dots \boldsymbol{z}\left(\left\lfloor \frac{N_{sc}^{DL}}{M} \right\rfloor - 1\right)\right]$, $\boldsymbol{z}(p) =< \boldsymbol{y}(Mp + 0), \boldsymbol{y}(Mp + 1), \dots \boldsymbol{y}(Mp + M - 1) >$ and $\boldsymbol{y_{leftover}}$ denotes the last elements of $\boldsymbol{y}$ not part of $\boldsymbol{z}$.
2) The number of rows of the sub-block interleaver, $R_{subblock}^{TC} = C$, equals the number of codeblocks for the configured TBS for transmission; the number of columns $C_{subblock}^{TC}$ is the minimum integer satisfying $N_{sc}^{DL} \le (R_{subblock}^{TC} \mathrm{x} C_{subblock}^{TC})$.
3) Append $\boldsymbol{z}$ with <*NULL*> elements, as required to obtain $\boldsymbol{z}_{app}$.
4) Write the elements of the appended vector into the $(R_{subblock}^{TC} \mathrm{x} C_{subblock}^{TC})$-sized matrix in a row-by-row basis, with $z_{app}(0)$ in column 0 of row 0.
5) Apply a pseudo-random cyclic shift to each of the $C_{subblock}^{TC}$ columns.
6) Obtain $\boldsymbol{z}_{\Pi_{EnTV}} = \left[\boldsymbol{z}(\Pi_{EnTV}(0)), \boldsymbol{z}(\Pi_{EnTV}(1)), \dots, \boldsymbol{z}\left(\Pi_{EnTV}\left(\left\lfloor \frac{N_{sc}^{DL}}{M} \right\rfloor - 1\right)\right)\right]$ by reading the elements of the above $(R_{subblock}^{TC} \mathrm{x} C_{subblock}^{TC})$ matrix column-by-column, excluding the <*NULL*> elements.
7) Map $\boldsymbol{z}_{\Pi_{EnTV}}$ consecutively to the N_{sc}^{DL} data tones, starting with the lowest tone index.
8) Map $\boldsymbol{y}_{leftover}$ to the remaining tones.

Regarding the size of the tone bundles, M, that will be interleaved this parameter can be chosen so that the frequency interleaver operates on either/or a per-tone basis or per-group-of-tones basis, where the group size can be 1 RB, for example.

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[2] N_{sc}^{DL} is the number of data tones that are used for transmission.

3. Performance evaluation

3.1. LTE-based 5G Terrestrial Broadcast in terrestrial channels

This section presents performance evaluation simulation results of time and frequency interleavers described in Section 2 over terrestrial channels for LTE-based 5G Terrestrial Broadcast. The simulation parameters for each of the evaluations are in the Annex.

3.1.1. Frequency interleaving performance evaluation

The study in [3] addresses the performance of frequency (tone) interleaving for the numerology for Physical Multicast Channel (PMCH) to support rooftop reception with 300 µs Cyclic Prefix (CP).

As discussed in Section 2.2, for large TBS, various codeblocks are transmitted in a slot/subframe, where each codeblock only spans a fraction of the entire frequency bandwidth. In rooftop reception with Single Frequency Network (SFN) configuration, the delay spread of the channel causes frequency selectivity that can erase entire codeblocks. To address this problem, frequency interleaving spreads the information of each codeblock across the entire system bandwidth.

Figure 3.1.1-1 shows the Link Level Simulation (LLS) results for TBS sizes of 45352 bits and 76208 bits (with 8 and 13 codewords, respectively) with an RS pattern of Df =3 and Dt =4 for a 10 MHz system bandwidth. The channel model represents a channel profile with Non-Line of Sight (NLOS) with a 35µs of delay spread representative of a MPMT network deployment. The gains due to the introduction of frequency interleaving are summarised in Table 3.1.1-1.

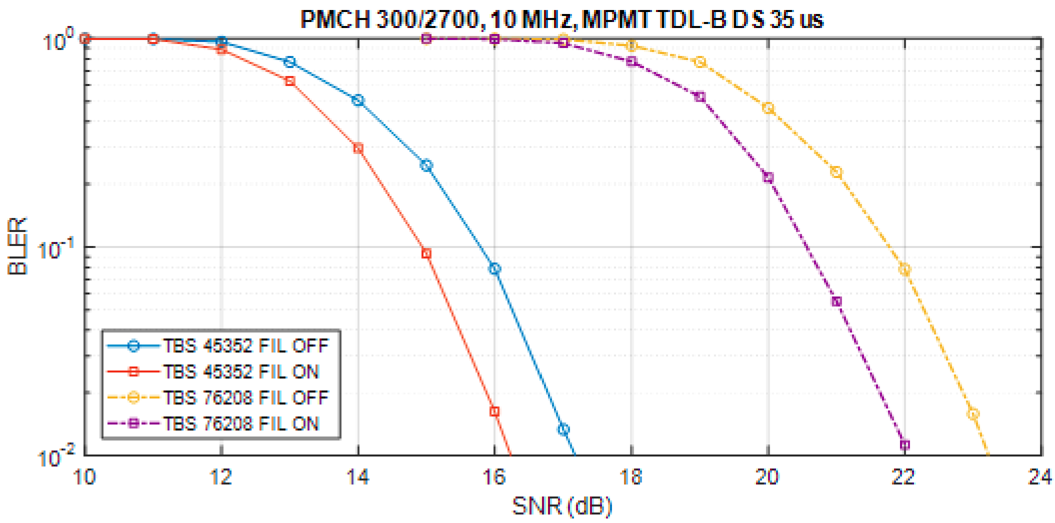

Figure 3.1.1-1: Performance of enhanced 5G Broadcast with frequency interleaving.

Table 3.1.1-1: Required SNRs for BLER, and gains (in parentheses) with interleaver.

TBS	Baseline 5GB	Frequency interleaving
76208	23.2 dB	22 dB ***(1.2 dB gain)***
45352	17.1 dB	16.3 dB ***(0.8 dB gain)***

3.1.2. Time interleaving performance evaluation

The link level performance of HARQ-based time-interleaving in mobile environments was first studied in [4]. The LLS results in [4] were crosschecked by an independent implementation in[6]. Figure 3.2.2-1 from [6] shows the link level performance of HARQ-based time interleaving for a user speed of 250 kmph with a 5 MHz system bandwidth. The schemes lacking time-interleaving with a TBS of 4968 bits (MCS 6) and TBS of 6456 bits (MCS 8) provide a spectral efficiency of 0.99 bits/s/Hz and 1.29 bits/s/Hz, therefore the results are comparable with those reported in [4]. The channel model represents a channel profile with Non-Line of Sight (NLOS) with a 20µs of delay spread representative of a LPLT network deployment. The results verify that at the high-speed scenario, HARQ-based interleaving can provide a spectral efficiency increase close to 30%. The significant gains due to time interleaving are summarised in Table 3.1.2-1. Additional simulation results in mobile environments for different MCS values are provided in [7].

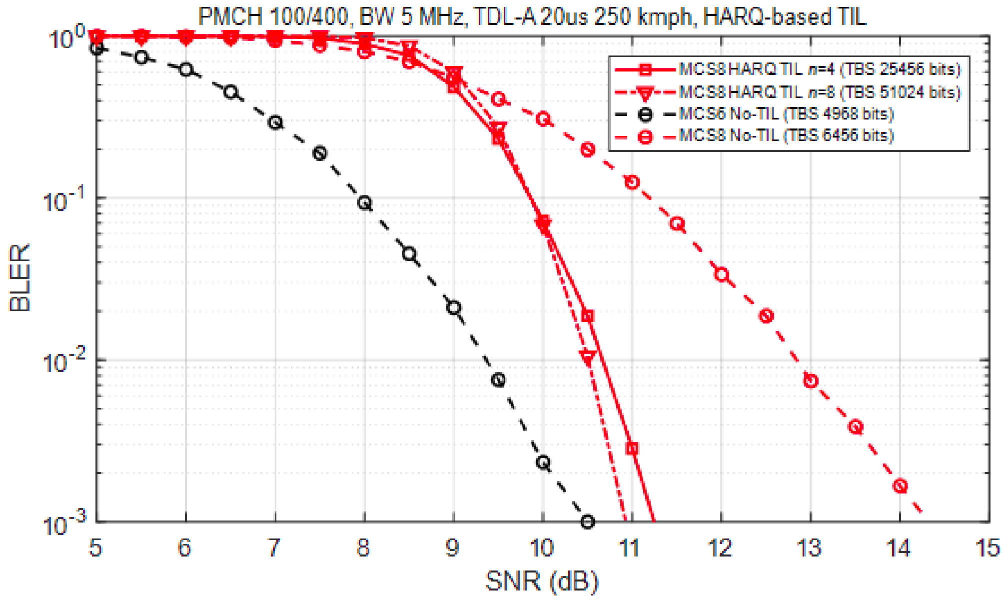

Figure 3.1.2-1: Performance of enhanced 5G Broadcast with time interleaving.

Table 3.1.2-1: Required SNRs for BLER, and gains (in parentheses) with interleaver for 250 km/h.

TBS	Baseline 5GB	4RV T/F Intlv.	8RV T/F Intlv.
6456 (MCS 8)	14.3 dB	11.3 dB **(*3 dB gain*)**	10.9 dB **(*3.4 dB gain*)**

3.1.3. Time/frequency interleaving and multiple Rx antennas performance evaluation

Reference [8] assesses the performance of LTE-based 5G terrestrial broadcast under the mobile India-Urban fading channel described in [9]and show how time/frequency interleaving enhancements can benefit LTE-based 5G broadcast. The channel model represents a channel profile with Non-Line of Sight (NLOS) with delay spread representative of a LPLT network deployment.

Figure 3.1.3-1 shows the performance comparison between *baseline* 5G Broadcast and versions incorporating the proposed time and frequency interleavers in [4]. For the time interleaving scheme, in the plot on the left a 4 RV-based interleaver with a depth of 128 ms is used. This effectively means that each TB samples the channel uniformly, every 32 ms. For the frequency interleaver, an interleaving depth of 686 tones is used, to provide maximal frequency spreading of codeblocks. On the right appears the performance of an 8 RV-based interleaver, in which the channel sampling periodicity is still 32 ms, but the interleaving depth is doubled with respect to the 4 RV case, to 256 ms. The frequency interleaving depth in the 8 RV-based time interleaving scenario is set to 383 tones.

From Figure 3.1.3-1 for the 4RV setting using only the time interleaver, gains of 0.2, 3.1, and 3.6 dB can be obtained with respect to baseline 5G Broadcast for 3, 40, and 120 km/h, which shows that especially at higher speeds, introducing a time interleaver in 5G Broadcast is beneficial. When a frequency interleaver is added on top of the time interleaver, joint exploitation of time and frequency diversity is achieved, which boosts the BLER-vs-SNR performance. For the 4 RV setting, further gains of 1.2, 0.8, and 0.5 dB can be obtained for the above-mentioned speeds. Additionally, as shown for the 8 RV setting in Figure 3.1.3-1, when the time interleaving depth is doubled, further gains are achieved, compared to the 4 RV setting. These results for different interleaver configurations are summarized in Table 3.1.3-1 below.

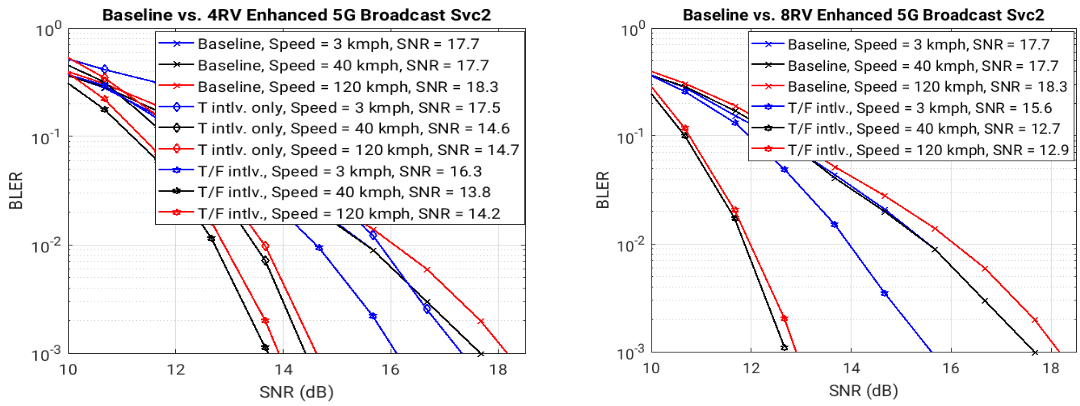

Figure 3.1.3-1: Performance of enhanced 5G Broadcast with proposed interleavers.

Table 3.1.3-1: Required SNRs for BLER, and gains (in parentheses) with interleavers.

Speed	Baseline 5GB	4 RV Time Intlv. only	4 RV T/F Intlv.	8 RV T/F Intlv.
3 kmph	17.7 dB	17.5 dB **(*0.2 dB gain*)**	16.3 dB **(*1.4 dB gain*)**	15.6 dB **(*2.1 dB gain*)**
40 kmph	17.7 dB	14.6 dB **(*3.1 dB gain*)**	13.8 dB **(*3.9 dB gain*)**	12.7 dB **(*5 dB gain*)**
120 kmph	18.3 dB	14.7 dB **(*3.6 dB gain*)**	14.2 dB **(*4.1 dB gain*)**	12.9 dB **(*5.4 dB gain*)**

Previously, was described how a feature present in traditional broadcast standards (time-frequency interleaving) can be added to 5G Broadcast by carefully reusing cellular building blocks.

Additionally, in the following It is described how a native feature in cellular standards and products for more than a decade (receiver antenna diversity) can be leveraged, in conjunction with the designs presented above, to enhance broadcast reception. In Figure 3.1.3-2 is displayed the performance with 2Rx antennas, of the same scenario as in the previous section, assuming low-correlation antennas.

The obtained gains vary between 5.4 to 6.7 dB for the different speeds, when compared against the single antenna results presented in the previous section. This exemplifies that, beyond the expected receive power gain of 3 dB, the use of 2 Rx antennas can exploit spatial diversity, which provides further gains on top of time and frequency interleavers.

Compared to the baseline, Table 3.1.3-2 shows the gains when incorporating frequency and time interleaving with 8 RV for 2 Rx antennas. The resulting gains varies between 8.8 dB and 11.3 dB for different speeds. This demonstrates the great benefits in power gain that interleaving (frequency and time) and 2 Rx antennas can achieve.

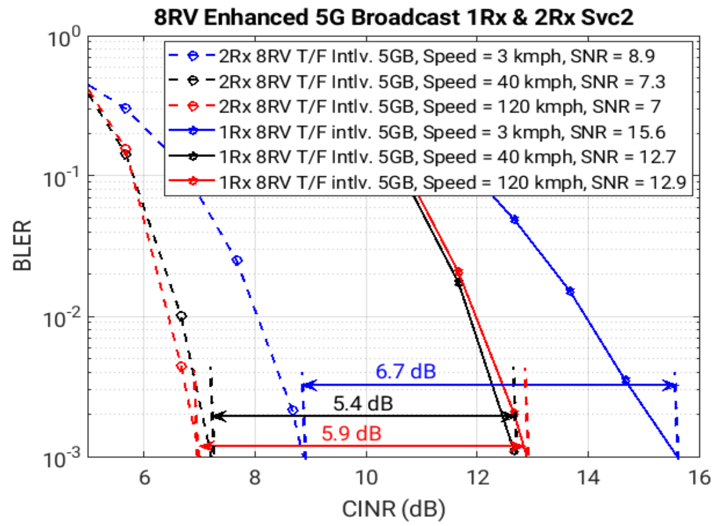

Figure 3.1.3.-2: Gains from 2Rx antennas.

Table 3.1.3-2: Required SNRs for BLER, and gains (in parentheses) with 2Rx antenna

Speed	Baseline 5GB	8 RV T/F Intlv. 1 Rx	8 RV T/F Intlv. 2 Rx
3 kmph	17.7 dB	15.6 dB **(*2.1 dB gain*)**	8.9 dB **(*8.8 dB gain*)**
40 kmph	17.7 dB	12.7 dB **(*5 dB gain*)**	7.3 dB **(*10.4 dB gain*)**
120 kmph	18.3 dB	12.9 dB **(*5.4 dB gain*)**	7 dB **(*11.3 dB gain*)**

3.1.4. Network planning considerations

Although diversity-harnessing techniques can result in large gains at very high speeds, from a LTE-based 5G Broadcast network deployment and planning perspective, the dimension needs to be done for the “"worst case” UE reception scenario. Network planning should not rely on the highest gains introduced by time interleaving, achieved for 120 km/h, since all UE moving at lower speed would fail to receive the content. Table 3.1.4-1 summarize the SNR needed for the baselines as well as enhanced LTE-based 5G Broadcast systems, for UE with both one and two Rx antennas.

From Table 3.1.4-1 it is obvious that for the worst-case scenario with time and frequency interleaving (corresponding to a speed of 3 km/h) the gains are much lower than the ones for higher speeds. Also, 2 Rx antennas provides much larger gains than adding interleavers to the system with 1 Rx.

Considering the worst-case SNR, **a significant 2.5 dB gain can be achieved** for a system with 2 Rx and T/F interleaving (SNR of 8.9 dB) compared to 2 Rx Baseline (SNR of 11.4 dB).

Table 3.1.4-1: 1Rx and 2Rx SNRs (at 10 -3 BLER cutoff), and SNRs for network planning

Speed	1Rx Baseline.	1 RX + 8 RV T/F Intlv.	2 RX Baseline	2RX + 8 RV T/F Intlv.
3 kmph	17.7 dB	15.6 dB	10.7 dB	8.9 dB
40 kmph	17.7 dB	12.7 dB	10.9 dB	7.3 dB
120 kmph	18.3 dB	12.9 dB	11.4 dB	7 dB
Worst-case SNR	*18.3 dB*	*15.6 dB*	*11.4 dB*	*8.9 dB*

3.2. 5G NR Multicast Broadcast Services (NR MBS): MBS Broadcast in terrestrial channels

The application of time interleaving to NR Multicast and Broadcast Services (NR MBS) Broadcast was first proposed in [10]. Using the same architecture and procedures as described in Section 2.2 and Section 2.3 of this document to the Group-Common Physical Downlink Shared Channel (GC-PDSCH) [10] demonstrates that significant performance improvements can be achieved in mobile channels.

Figure 3.2-1 shows the LLS results for MBS Broadcast with time interleaving, with 4 RVs, and 16 TBs interleaved with each other. The channel model represents a channel profile with NLOS with a 100ns of delay spread representative of a LPLT network deployment. Simulation parameters are summarized in the Annex.

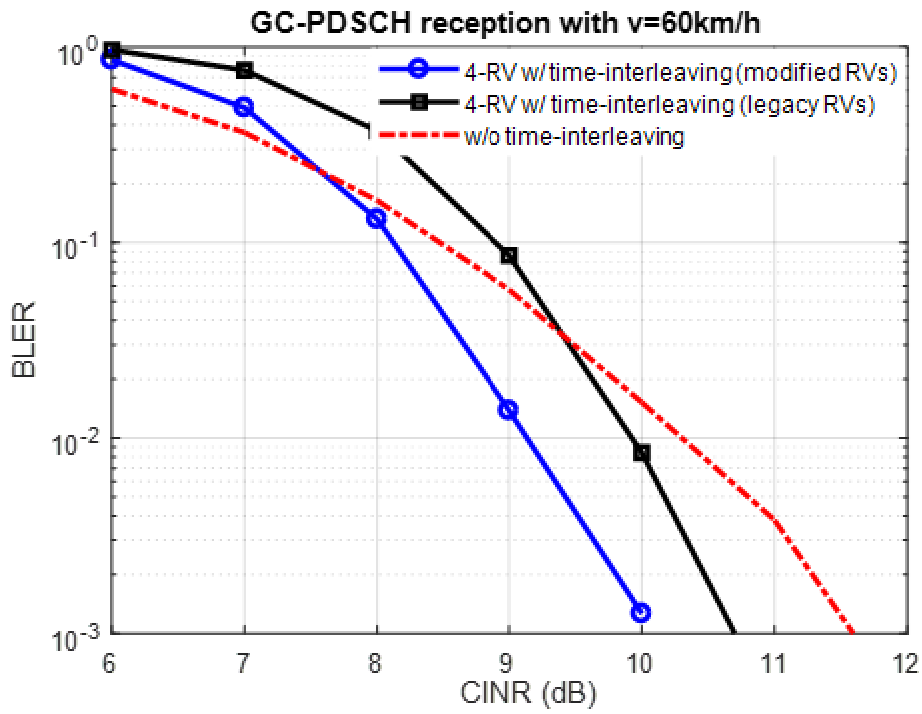

Figure 3.2.-1: BLER performance of broadcast GC-PDSCH with 4-RV repetitions.

The results from Figure 3.2-1 confirm the performance improvement due to the implementation of the proposed time-interleaving for broadcast GC-PDSCH. The time-interleaving for GC-PDSCH repetitions with modified RVs can achieve ~1.5dB gain at BLER=0.1% over non-interleaved transmission, as well as a ~1 dB gain over interleaved transmission with legacy RV definition.

Table 3.2.-1: Required SNRs for BLER, and gains (in parentheses) with interleaver for 60 km/h.

Modulation/Code Rate	Baseline NR MBS Broadcast	4 RVs Time Intlv. (legacy RV definition)	4 RVs Time Intlv. (modified RVs)
16QAM/0.4785	11.6 dB	10.7 dB ***(0.9 dB gain)***	10 dB ***(1.5 dB gain)***

4. Potential 3GPP specification impact

In terms of specification impact, changes on UE procedures receiving the physical channels and payload bits generation (TS 36.213 and TS 38.214 for LTE and NR, respectively), mapping of modulated symbols to time-frequency resources (TS 36.211 and TS 38.211 for LTE and NR, respectively), the definition of modified redundancy versions (TS 36.212 and TS 38.212 for LTE and NR, respectively), and higher layer signalling aspects (TS 36.331 and TS 38.331 for LTE and NR, respectively) is anticipated. In particular:

- For time-interleaving
    - The physical layer procedures for the UE receiving the PMCH (for LTE-based 5G Broadcast) and PDSCH (for NR MBS) will need to reflect the fact that a time-interleaved TB will be received over multiple (interleaved) slots/subframes, in accordance with the interleaving pattern (e.g., how many TBs are interleaved together, the depth of interleaving, etc.)
        - It may further be specified, as part of this PMCH/PDSCH reception procedure, that for time-interleaved broadcast reception, the UE is not expected to decode a TB until it has received the last RV corresponding to the TB (since all RVs will be required for decoding)
    - The mapping of the modulated symbols to time-frequency resources, for a given TB, will need to be specified in accordance with the time-interleaving pattern that is used.
    - The generation of number of payload bits—accounting for the TBS scaling described previously—will also need to be reflected.
    - The definition of the "modified" redundancy versions—as described and motivated in Section 2.3—will need to be specified during the generation of rate-matched bits, within the multiplexing and channel coding specifications.

- For frequency-interleaving
    - Tone or set-of-tones level frequency interleaving will need to be specified as part of mapping the modulated symbols to physical (time and frequency) resources.

- With respect to higher layer configurations
    - Enabling/Disabling of interleaved transmission modes may be configured.
    - One out of several possible interleaving configurations (e.g., time interleaving depth, number of interleaved TBs, granularity of frequency interleaving, etc.) may be configured.

5. Conclusions

Based on the discussions in this report the following conclusions are made:

- Time and frequency interleavers are crucial components of wireless broadcast standards to increase the transmission robustness in time-varying channels (e.g., mobile reception) and frequency selective channels (e.g., SFN deployments).

- Time and frequency interleavers are standardised features for broadcasting standards such as DVB-T2 and ATSC 3.0.

- For 3GPP systems, it is possible to design time and frequency interleavers on top of the existing broadcast functionality while respecting constraints on hardware reuse:
    - time interleaving can be implemented by reusing the HARQ retransmissions/combining cellular building block; and
    - frequency interleaving can be implemented by interleaving tones or set-of-tones corresponding to the codeblocks.

- Performance evaluation of time and frequency interleaving for broadcast services with 3GPP systems in representative terrestrial channel environments have shown significant performance improvements.

- For LTE-based 5G Broadcast with 2 antenna receivers, time-frequency interleaving can provide gains of various dBs in terms of required SNR at high-speed scenarios: up to 4.4 dBs with 8 RVs at 120 kmph are reported. Taking into account network planning considerations where UEs with low and high speeds conditions need to be covered, still significant gains of up to 2.5 dBs in required SNR are reported by the implementation of time-frequency interleaving.

- For NR MBS Broadcast with 2 antenna receivers, reported results show that time interleaving provides gains up to 1.5 dBs in required SNR at 60 kmph with 4 RVs.

- Expected specification impact to introduce time and frequency interleaving for broadcast services in 3GPP systems has been detailed.

This version of the report has focused on terrestrial networks for LTE-based 5G Broadcast and NR MBS Broadcast. However, the technologies addressed therein may also be applicable to Non-Terrestrial Networks subject to corresponding modifications. Further analysis may be provided in a future version of this report. Interested experts are invited to contribute to such study.

Feedback to this version of the report can be provided in https://github.com/5G-MAG/Requests-for-Feedback.

6. Related documentation

[1] R1-1913095, “Information on Time Interleaving in State-of-the-Art Terrestrial Broadcast Systems”, EBU, BBC, IRT, ABS, NHK, 3GPP RAN WG1, #99, Reno, USA, November 2019.

[2] A/322:2023-03, “Physical Layer Protocol”, ATSC, March 2023.

[3] R1-1911355, “Time and Frequency Interleaving for LTE-based 5G Terrestrial Broadcast”, by EBU, BBC, IRT, in RAN198b.

[4] R1-1912692, “Numerology with 100us CP”, Qualcomm Incorporated, 3GPP RAN WG1, #99, Reno, USA, November 2019.

[5] R1-1908841, Support of longer numerologies for rooftop reception, Qualcomm Incorporated, 3GPP TSG RAN WG1 Meeting #98.

[6] R1-1913343, "On the performance evaluation of HARQ-based time-interleaving for LTE-based 5G terrestrial broadcast”, EBU, BBC and IRT, 3GPP RAN WG1, #99, Reno, USA, November 2019.

[7] *Performance of 5G Broadcast and benefits of proposed time-interleaving enhancements*, David Vargas, Simon Elliott, Oliver Haffenden, Ryan McCartney, Andrew Murphy, Jordi Joan Gimenez, IBC 2020. Link

[8] *5G Broadcast Receivers: Optimizing Performance under Implementation Constraints*, Ayan Sengupta, Javier Rodriguez Fernandez, Alberto Rico Alvarino, Thomas Stockhammer, IBC 2023. Link

[9] S.-K. Ahn et al., "Evaluation of ATSC 3.0 and 3GPP Rel-17 5G Broadcasting Systems for Mobile Handheld Applications," in IEEE Transactions on Broadcasting, vol. 69, no. 2, pp. 338-356, June 2023. Link

[10] R1-2101489, “Discussion on broadcast/multicast for RRC_IDLE and RRC_INACTIVE UEs”, by Qualcomm Incorporated, 3GPP TSG RAN WG1 #104, February 2021.

7. Annexes

7.1. Acronyms

3GPP	3rd Generation Partnership Project
ATSC	Advanced Television Systems Committee
BLER	BLock Error Rate
CP	Cyclic Prefix
CRBI	Cross-Row Block Interleaver
CTI	Convolutional Time Interleaver
DVB	Digital Video Broadcasting
FEC	Forward Error Correction
FFT	Fast Fourier Transform
HARQ	Hybrid Automatic Repeat reQuest
HPHT	High Power High Tower
LLR	Log-Likelihood Ratio
LLS	Link Level Simulator
LMMSE	Linear Minimum Mean Square Error
LPLT	Low Power Low Tower
LTE	Long Term Evolution
MAG	Media Access Group
MCS	Modulation Coding Scheme
MBS	Multicast Broadcast Service
MPMT	Medium Power Medium Tower
NLoS	Non-Light of Sight
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplex
PMCH	Physical Downlink Shared Channel
PDSCH	Physical Multicast Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RV	Redundancy Version
SNR	Signal-to-Noise-Ratio
TBS	Transport Block Size
TFI	Time Frequency Interleaver
TTI	Transmission Time Interval

7.2. Simulation Parameters for LTE-based 5G Terrestrial Broadcast

Table 8.2-1: Simulation Parameters for Sections 3.1.1 to 3.1.3

Parameter	Freq. interleaving parameters Section 3.1.1	Time interleaving parameters Section 3.1.2	Time and freq. interleaving parameters Section 3.1.3
System Bandwidth (MHz)	10	5	8
Useful BW (MHz)	9	4.5	7.2
FFT length	15369	7680	12288
Subcarrier Spacing (kHz)	0.37	2.5	1.25
Sampling rate (MHz)	15.36	7.68	15.36
OFDM symbol duration (us)	2700	400	800
CP duration (us)	300	100	200
Channel model	TDL-B (Delay spread 35 us)	TDL-A (Delay spread 20 us)	India-Urban
Network topology	MPMT	LPLT	LPLT
Channel estimation	Least-Squares	Least-Squares	LMMSE over 48 consecutive pilots per RB bundle
Number of Rx antennas	1	2	1 or 2
Pilot pattern stagger	(Fd3, Td4)	(Fd2, Td2)	(Fd3, Td2)
Time (T) and/or Frequency (F) interleaver	Frequency interleaving evaluated	Time and Frequency interleavers evaluated	Time and/or Frequency interleaver evaluated
Modulation	64QAM	16QAM	QPSK (Svc 1) and 16-QAM (Svc 2)
TBS and MCS	45352 and 76208	4968 and 6456	5544 (Svc1) and 10296 (Svc2)
Code Rate	0.55 and 0.57	0.48 and 0.65	0.53
MCS	MCS 17 and MCS 23	MCS6 and MCS8	-

7.3. Simulation Parameters for NR MBS Broadcast

Table 8.3-1: Simulation Parameters (Section 3.2)

Carrier Frequency	2GHz
Subcarrier spacing	15kHz
Bandwidth	20MHz
Channel model	TDL-C with RMS delay spread=100ns
Antenna configuration	2T2R
Transmission scheme	single port precoder cycling
DMRS	2 symbols
MIMO layer	1
Coding rate	0.4785
Modulation	16QAM
PDSCH repetition number	4
UE mobility speed	60km/h

History

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