5G BROADCAST RECEIVERS: OPTIMIZING PERFORMANCE UNDER IMPLEMENTATION CONSTRAINTS

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ABSTRACT

The holy grail of making broadcast services ubiquitously available to the broadest set of users is to enable reception directly to smartphones, while reusing the silicon of cellular modems, with minimal compromises towards efficiency for a broad set of use cases.

5G Terrestrial Broadcast, as specified in 3GPP and profiled in ETSI TS 103 720, is realizing this promise. In the first part of our paper, we provide an overview of the design philosophy behind 5G Broadcast, mainly re-use of existing cellular modem silicon and protocol stack. For efficiency demonstration, we provide comparative simulations against other broadcasting standards under several practical deployment scenarios, further backed by multiple successful demos and trials of the technology.

Next, we highlight that, while maintaining the constraint of hardware reuse, further enhancements to the technology can be introduced by carefully exploiting existing features in cellular modems – for instance, time interleaving can be realized by reusing the building blocks of HARQ combining. Along with the incorporation of a codeblock-spreading frequency interleaver, we demonstrate considerable performance improvements in high-mobility scenarios, when such time interleavers are used.

We finally evaluate how some basic features of cellular modems (e.g., receive diversity) can greatly improve the performance of 5G Broadcast beyond the basic broadcast-specific feature set.

INTRODUCTION

3GPP-based Multimedia Broadcast Multicast Services (MBMS) for mobile network operators (MNO) has been part of 3GPP specifications for more than 20 years. In Release 9, an LTE-based MBMS, referred to as "eMBMS" was created and further enhanced until Release-12. In the last decade, several MNOs deployed eMBMS within operators' networks and eMBMS modems and service layers are prominently available on mobile chipsets and mainstream mobile devices – primarily also because they are hardware-compatible with LTE modems. Meanwhile, with the 3GPP expansion to verticals and the migration to 5G, broadcasters showed significant interest in using 3GPP-based technologies to be operated on dedicated broadcast networks and a set of dedicated requirements of broadcast service providers finally resulted in the definition of 5G Broadcast requirements documented in clause 6.13 of 3GPP TS 22 261.

Based on these requirements, 3GPP specifications have gradually evolved (through to Release 16) to meet the use cases and requirements in order to support broadcasting of linear television and radio services, taking into account among others, support of free-to-air (FTA) services over 3GPP with no MNO broadcast subscription; support of receive-only mode devices (ROM); decoupling of content, MBMS service and MBMS transport functions; support of dedicated, downlink-only networks; and support of single frequency networks (SFNs) with large inter-site distances. Finally, in Rel-17 and Rel-18 of 3GPP, additional specific needs for broadcast channel bandwidths of 6/7/8 MHz, support for UHF spectrum and the addition of public warning and emergency alerts are addressed.

While 3GPP could have taken a radical approach to define a clean slate radio system to meet the broadcasters' requirements, a more pragmatic route was chosen: experiences from the past with dedicated modems such as MediaFLO or DVB-H, and the need for easy integration into mainstream mobile devices, led to the decision to evolve eMBMS to LTE-based 5G Broadcast instead of any radical new designs. The term *hardware-compatible feature* was coined in the process, i.e., LTE-based 5G Broadcast was *developed with the cellular modem architecture in mind*: the new features added to the physical and higher layers were carefully designed to be compatible with the *cellular modems* that are in our smartphones today. To support reception from broadcast networks, such as a high-power high-tower downlink-only infrastructure, existing hardware in smartphones can be entirely reused. With this integration, typical commercial assessments before adding a new modem technology to a mainstream mobile chipset can be cut short or completely bypassed: for example, a detailed analysis of the technology in terms required area size, hardware availability, power consumption, integration with the apps and operating systems, global harmonization, development timescales, co-existence and re-use of existing functions, testing and interoperability testing, and many more.

Based on all these considerations, 5G Broadcast can be viewed as a modem feature, like many other technology enhancements in 3GPP, that reuses the basic building blocks of a cellular modem. With this, many new opportunities may arise. For example, this could almost instantly expand the reach that broadcasters can have, in terms of access to the millions of (3GPP standards' compliant) smartphones all over the world, that are—and will be—in people's pockets now and for the years and decades to come.

Based on this introduction, this paper addresses the following main contributions:

1. Provide a summary of the technology extensions to meet the broadcast requirements for LTE-based 5G Broadcast, to meet the main design target & "reason for being" of 5G broadcast, namely, to enable operation of a broadcast network (including high-power high-tower) where the receivers are hardware-compatible with cellular modems.

2. Providing an analysis of 5G Broadcast over different physical environments of practical interest for broadcasters. To evaluate the performance of a hardware-compatible design compared to an unconstrained design, we provide an estimate of the gains that certain features would provide, as compared to currently specified 5G Broadcast.

3. We provide examples of how additional enhancements can be added to 5G Broadcast in a hardware-compatible manner by reusing some cellular building blocks (e.g., HARQ combining) to realize features present in broadcast standards

(e.g., time-interleaving). We also assess the performance impact of utilizing the basic cellular feature of receiver antenna diversity on broadcast performance.

Real world demos of 5G Broadcast

In the last few years, several real-world demonstrations of 5G Broadcast have occurred. The main objective of these activities is to showcase how devices with off-the-shelf cellular hardware can receive media and data directly from broadcast infrastructure in UHF broadcast spectrum in receive-only mode. Some specific use cases such as ad insertion, datacasting and seamless unicast / broadcast switching have been also demonstrated. Additional information on these activities can be found in [7, 8, 9] among others.

OVERVIEW OF 5G BROADCAST – HARDWARE-COMPATIBLE EXTENSIONS

For a comprehensive overview of the 5G Broadcast standards from 3GPP Release 9 through Release 16, with a focus on physical layer evolution, we refer the reader to the review article in [6]. Below, we provide a summary of the features that were introduced under 5G Broadcast to meet the necessary requirements of broadcasters, while leveraging the basic building blocks of cellular technology.

One of the major requirements brought forward by broadcasters was the possibility of deploying a downlink-only network that is dedicated to broadcast. To realize this requirement, the number of available MBSFN subframes was increased. The cellular synchronization signals were kept unchanged, but its periodicity was modified to reduce the overhead, hence enabling the reuse of the *searcher* hardware and procedures for broadcast. To increase the coverage of control channels, larger aggregation levels (w.r.t. legacy LTE) for PDCCH and cross-slot combining for PBCH reception were specified.

On supporting broadcast infrastructure, one of the major features is the introduction of new numerologies for support of single frequency networks with a large inter-site distance (for mobile devices, rooftop antennas and car-mounted receivers). These numerologies were carefully selected to be consistent with the frame structure of cellular systems to minimize the impact on implementations. The modulation and coding chain used for unicast communications was kept unchanged for these new numerologies, which enables the reuse of hardware decoders already present in the cellular modem.

Other system-level modifications introduced include the possibility of operating in receive-only mode (i.e., a device that does not communicate with the network prior to receiving broadcast—a first time in 3GPP) or support of *transparent mode* in which 3GPP is used as an IP transport network and enables the use of service layers not defined in 3GPP.

PERFORMANCE COMPARISON OF 5G BROADCAST WITH ATSC 3.0

As described above, the most attractive feature of 5G broadcast is the possibility of directly reaching smartphones that are using current cellular mobile chipsets.

In this section, we show that even with the constraint of cellular hardware reuse, the currently specified version of 5G Broadcast by 3GPP offers competitive performance when compared to an unconstrained system such as ATSC 3.0.

Evaluation setup

In Table 1, we provide a description of the physical layer parameters used to compare the performance of ATSC 3.0 and 5G broadcast.

From **Table** 1, we observe that while both ATSC 3.0 and 5G Broadcast operate under a system bandwidth of 8 MHz, the useful bandwidths are 7.78 MHz and 7.2 MHz respectively. For a fair comparison, an SNR boost of 0.33 dB ($10 \cdot \log_{10}(7.78/7.2)$) is applied to 5G Broadcast, ensuring that the same total transmit power as ATSC 3.0 is used.

Table 1**: Parameters for simulation of ATSC 3.0 and 5G broadcast.**

Parameter	**ATSC 3.0**	**5G Broadcast**
System Bandwidth (MHz)	8	8
Useful BW (MHz)	7.78	7.2
FFT length	8192	12288
Subcarrier Spacing (kHz)	1.125	1.25
Sampling rate (MHz)	9.216	15.36
OFDM symbol duration (us)	889	800
CP duration (us)	222.2	200
Channel estimation	LMMSE over 48 consecutive pilots per RB bundle	
Number of Rx antennas	1 (unless specified otherwise)	
Pilot pattern stagger	(Fd3, Td2)	(Fd3, Td2)
Time (T) and/or Frequency (F) interleaver	F interleaver: ON T interleaver: 400 ms extended CTI	None
Modulation	QPSK (Svc 1) NUC 16-QAM (Svc 2)	QPSK (Svc 1) 16-QAM (Svc 2)
Coding	8/15 LDPC 64800 + BCH	≈8/15 Turbo
TBS	34368	5544 (Svc 1) 10296 (Svc 2)
Throughput	~5 Mbps for Svc1 and ~10 Mbps for Svc 2	

Performance over AWGN channels

We provide a first comparison between ATSC 3.0 and 5G Broadcast over an AWGN channel. This comparison allows us to isolate the performance difference between both standards in terms of their core channel coding and modulation technologies (e.g., usage of long LDPC codes and BCH codes in ATSC 3.0 vs short turbo codes in 5G Broadcast).

The performance comparison for Svc 1 and Svc 2 is provided in Figure 1. In this case, the advanced BICM technologies of ATSC 3.0 results in a performance difference of 0.8 dB for Svc 1 with QPSK modulation, and 0.7 dB for Svc 2 with NUC 16-QAM constellation.

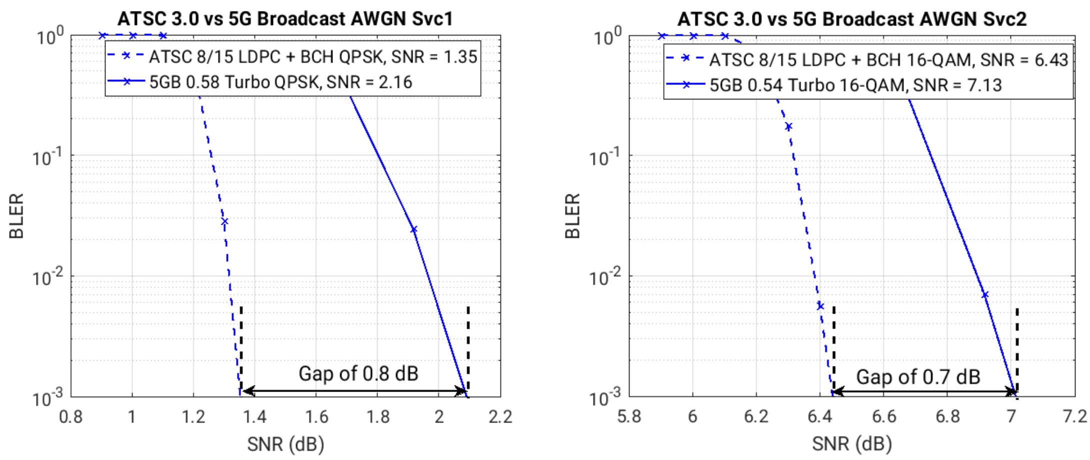

Figure 1: Comparison for Svc 1 and Svc 2 under an AWGN channel.

Performance over multipath channels with line-of-sight (LoS) paths

In the next evaluation, we analyse the performance difference between ATSC 3.0 and 5G Broadcast over a Rician fading channel. For this, we use the RC20 channel from [1].

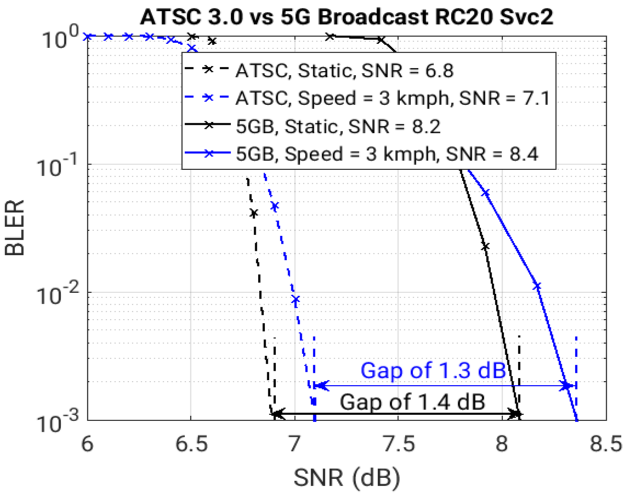

Figure 2: Rician channel comparisons.

From Figure 2, it can be observed that the performance gap between 5G Broadcast and ATSC 3.0 increases with respect to that in Figure 1, yielding a 1.4 and 1.3-dB gap under a static and fading RC20 channel, respectively. On top of the approximately 0.8 dB gap from BICM, the excess gain (at least for the static setting) comes from ATSC's frequency interleaver. Further, we observe that in the fading RC20 case, which corresponds to a user speed of 3 kmph, no additional gain is observed vis-à-vis the static setting. This indicates that, under this Rician channel with a reasonably powerful LoS component, the time diversity that ATSC 3.0 can harness using its Convolutional Time Interleaver (CTI) is negligible. We would expect similar performance trends and gaps whenever there is a LoS component in the channel.

Performance over non-line-of-sight (NLoS) multipath channels

Next, we analyse the performance difference between both standards over the NLoS RL20 channel [1]. The goal here is to further analyse how much gain the frequency and time interleavers in ATSC 3.0 provide with respect to 5G Broadcast. To this end, we present performance comparisons for the RL20 channel in Figure 3, for both Svc 1 and Svc 2.

From Figure 3, we observe that without the LoS component in the multipath channel, ATSC 3.0 offers additional performance benefits, with an additional 0.5 dB gap with respect to the 1.4 dB gap observed in the previous section when the LoS component was present. Notice, however, that even in a NLoS channel, the gain from using a frequency interleaver (in a static setting) is relatively small. We note that Svc 2 offers a larger gain for ATSC 3.0 since, at this data rate, the 5G Broadcast standard requires two codeblocks instead of one, which limits the frequency diversity experienced by each codeblock.

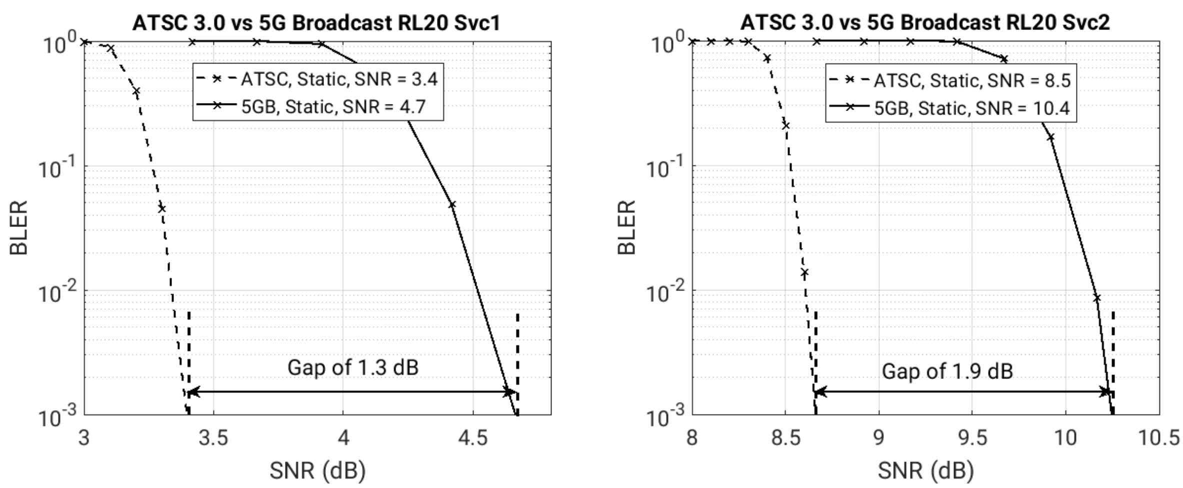

Figure 3: Comparisons of Svc 1 and Svc 2 over the RL20 static channel.

In Figure 4, we show a performance comparison between ATSC 3.0 and 5G Broadcast, over a *fading* NLoS channel, for a pedestrian UE (with a mobility of 3 kmph) in an urban environment [2]. Unlike the comparisons presented thus far, here we assume that the receivers for both ATSC 3.0 and 5G Broadcast are equipped with 2 receive (Rx) antennas. 2 Rx antennas—a basic feature in cellular modems—harness the spatial orders of diversity in a mobile environment, and result in a performance gap of 2 dB for 5G Broadcast, when compared against ATSC 3.0. In a later section, we shed more light on diversity reception with 2Rx antennas.

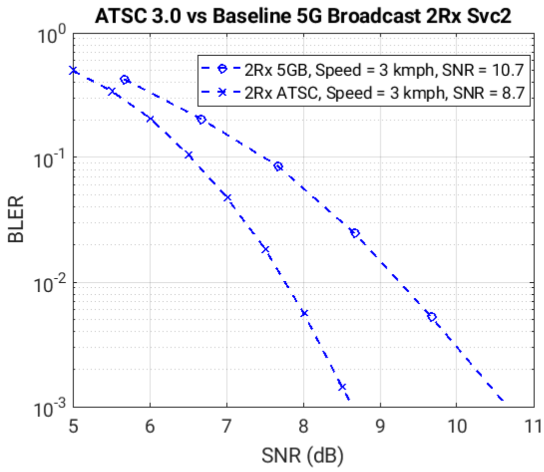

Figure 4: Comparison over fading NLoS channels with 2Rx antennas.

CELLULAR SILICON-FRIENDLY ENHANCEMENTS TO 5G BROADCAST

Despite the constraints of hardware reuse, it is possible to design additional broadcast-specific features on top of the current 5G Broadcast standard. 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, we present the design of a time interleaver by reusing the “HARQ combining” building block, present in all cellular modems.

Harnessing time diversity for 5G Broadcast was first proposed in 3GPP by [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 LLR buffer memory of the receiver. Indeed, in [3], it was proposed to only apply such a solution for small values of system bandwidth.

HARQ-based time interleaving and cellular modem-friendliness

We propose a design that provides time-diversity without increasing the LLR buffer memory at the receiver. The key to our 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 slots/subframes. For throughput parity with non-interleaved transmission, our TB size is scaled by n—the number of redundancy versions (RVs) used for each TB. With this approach, we 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 5, we depict this mechanism: 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.

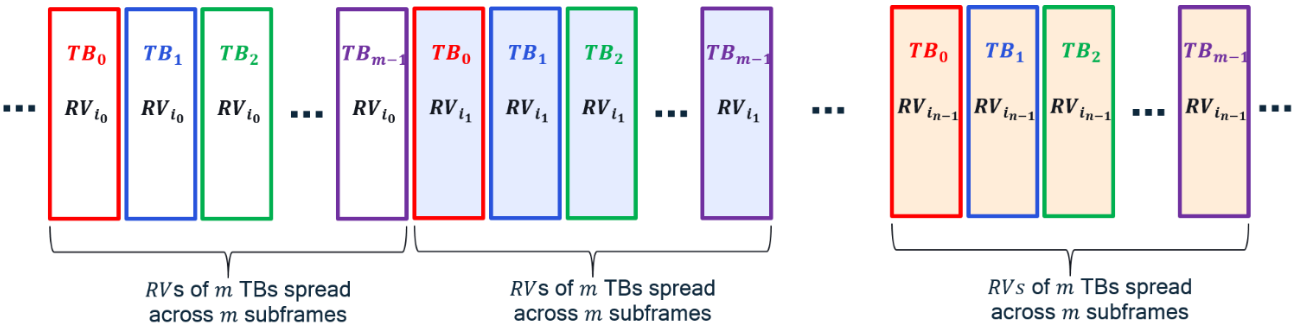

Figure 5: Interleaved transmission of "HARQ redundancy versions" of (scaled) transport blocks across slots/subframes.

As we will describe next, there are further nuances—notably, the generation of "modified redundancy versions"—that are integral to our 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]. As a result, we incorporate a tone-level frequency interleaver to spread out the codeblocks in frequency.

DETAILS OF TIME AND FREQUENCY INTERLEAVING FOR 5G BROADCAST

Generating "continuous" redundancy versions of a TB

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

1) There are only 4 redundancy versions defined, which would limit the interleaving depth to $n \leq 4$ slots/subframes.
2) 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.

To overcome the above drawbacks, our design of "*modified*" RVs (Figure 6) ensures that the coded bits for RV_i start right after those for RV_{i-1}, and we are not restricted to 4 RVs.

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 our frequency interleaver are:

1) The tones corresponding to the codeblocks are written row-wise.
2) Pseudo-random shifts are applied to the columns.
3) Elements are read column-wise.

For a detailed standards' focused description on these aspects, we refer the reader to [5].

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, for $n = 4$, we use $\{RV_0, RV_2, RV_3, RV_1\}$ in sequence, while for $n = 8, \{RV_0, RV_4, RV_6, RV_2, RV_7, RV_3, RV_5, RV_1\}$ is used in sequence.

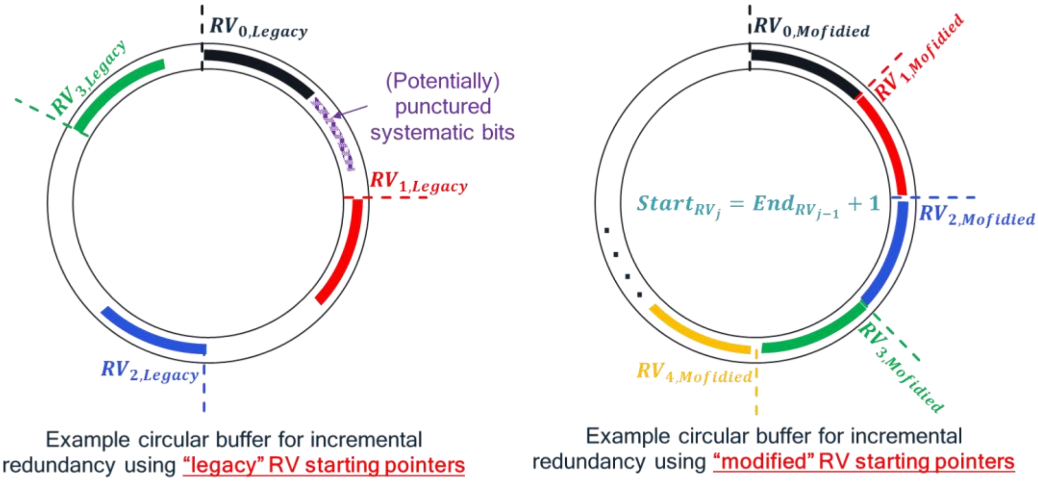

Figure 6: Illustration of "legacy" vs "continuous" RVs.

EVALUATION OF PROPOSED TIME AND FREQUENCY INTERLEAVING

In this section, we evaluate our time and frequency interleavers as described above. We assess their performance under the mobile India-Urban fading channel described in [2].

We show in Figure 7, the performance comparison between *baseline* 5G Broadcast and versions incorporating our proposed time and frequency interleavers. For our time interleaving scheme, in the plot on the left, we use a 4 RV-based interleaver with a depth of 128 ms. 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, we show 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 7, we observe that, 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 kmph, 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 7, when the time interleaving depth is doubled, further gains are achieved, compared to the 4 RV setting. These results are summarized in Table 2 below.

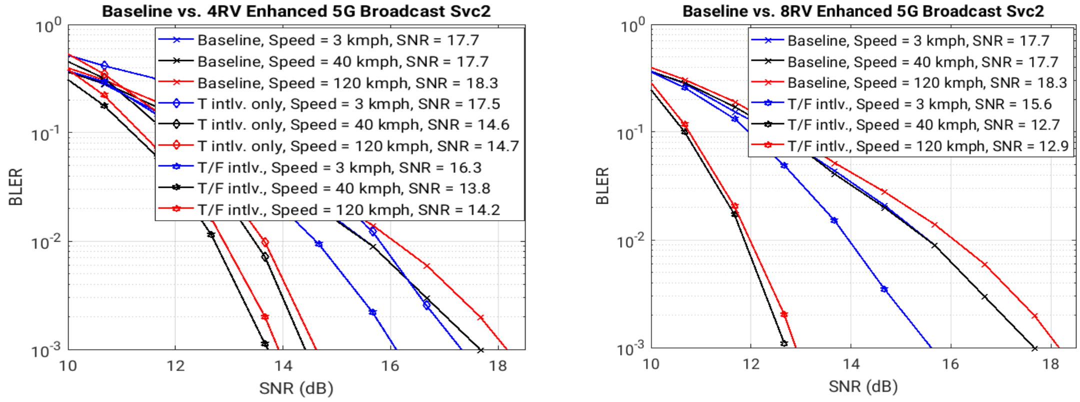

Figure 7: Performance of enhanced 5G Broadcast with proposed interleavers.

Table 2: Required SNRs for 10^{-3} 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***)

5G BROADCAST WITH DIVERSITY RECEPTION

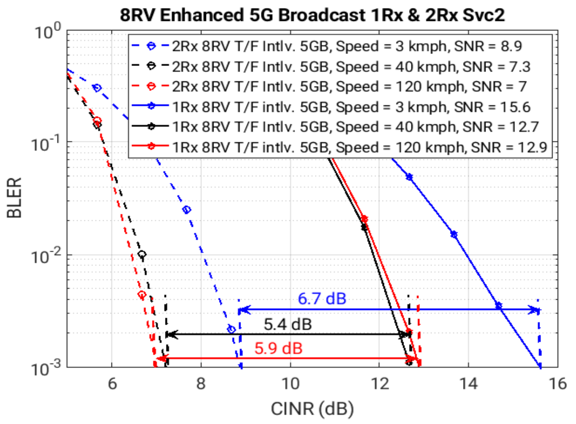

Figure 8: Gains from 2Rx antennas.

In the previous section we described how a feature present in traditional broadcast standards (time-frequency interleaving) can be added to 5G Broadcast by carefully reusing cellular building blocks.

Here we show 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 8, we show the performance with 2Rx antennas, of the same scenario as in the previous section, assuming low-correlation antennas.

We observe that, we gain 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.

NETWORK PLANNING CONSIDERATIONS

While we have demonstrated that cellular diversity-harnessing techniques can result in large gains at very high speeds, from a 5G Broadcast network deployment and planning perspective, we need to dimension the system for the “worst case” UE. For example, network planning should not rely on the time interleaving gains achieved in the 120 kmph scenario, since such a network would fail to serve a large number of receivers moving at lower speeds. In Table 3, we provide such worst-case SNR requirements for baseline as well as enhanced 5G Broadcast systems, for UEs with both with 1 Rx and 2 Rx antennas.

We observe that the gains from the time-frequency interleaving enhancements are much smaller from a “worst-case SNR” perspective. For instance, the *worst-case SNR gains* from the interleavers are 2.5—2.7 dB, while those for higher speeds (120 kmph) are 4.4—5.4 dB. Further, we see that 2Rx antennas provide an overall 6.7—7 dB gain in worst-case SNRs w.r.t the same system with 1Rx. Therefore, from an overall network planning perspective, the addition of 2 Rx to all receivers provides much larger gains than adding time interleavers to the system (which mainly benefit receivers moving at higher speeds).

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

	1Rx Baseline.	1Rx + 8 RV T/F Intlv.	2Rx Baseline	2Rx + 8 RV T/F Intlv.
SNR for 3 kmph	17.7 dB	15.6 dB	10.7 dB	8.9 dB
SNR for 40 kmph	17.7 dB	12.7 dB	10.9 dB	7.3 dB
SNR for 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***

CONCLUSION

The key design philosophy behind 5G Broadcast is to enable broadcast reception in devices with a cellular modem, without the need of additional hardware, thus enabling economies of scale and better integration with the smartphone ecosystem. In this paper, we provided insights on the design choices behind 5G Broadcast and showed performance comparisons against dedicated broadcast standards (ATSC 3.0).

We also explored how broadcast-native features (time interleaving) could be added to 5G Broadcast while maintaining the principle of hardware reuse, and how cellular-native features (dual antenna reception) can benefit broadcast reception.

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