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Practical Performance Analysis of Interference in DSS System

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Abstract: The 5G network is developing rapidly. However, due to spectrum resource limitation, it is expected to use the 5G network to ensure high resource utilization and network efficiency, while keeping part of 4G in the same band for existing 4G users. Dynamic spectrum-sharing (DSS) technology enables 4G/5G wireless networks to coexist in scarce spectrum resources and dynamically allocates spectrum resources in the same band. 4G/5G DSS has been successfully commercialized in some countries such as Germany and Brazil. However, complex 4G/5G DSS networks will introduce intra-frequency interference in the inter-system, which will affect network performance. Therefore, we innovatively proposed two interference mitigation schemes: buffer setting and rate matching. Furthermore, we have verified the practical performance of both schemes in a commercial network for the first time to determine the feasibility of the schemes. From theory, simulation, and practical analysis, both schemes can effectively mitigate the interference of the inter-system introduced by DSS: increasing the network rate by 60% in the interference environment and improving the user experience in the DSS architecture.

Keywords: dynamic spectrum sharing; 4G network; 5G network; interference mitigation; rate matching; buffer setting

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1. Introduction

As wireless communication continues to evolve and user demand increases, 5G technology is developing at high speed [1]. Based on comprehensive international spectrum planning and frequency band characteristics, the 5G network mainly works in the low-frequency band below 6 GHz or the high-frequency millimeter wave above 24 GHz. The low frequency includes part of long-term evolution (LTE) frequency bands [2]. The low-frequency band is conducive to the formation of effective continuous network coverage to meet the user experience requirements; the high frequency has affluent band resources, which can be used as an effective complement to the low frequency to meet the high rate and system capacity requirements in hot areas [3].

How to efficiently use the limited spectrum resources and promote efficient and rapid transition is a challenge that must be solved for mobile communication development [4,5]. This is specifically reflected in the following two aspects:

Firstly, how to achieve new radio (NR) low-frequency wide coverage: the spectrum is an important resource in wireless networks. Currently, almost all low-frequency spectrum resources are occupied by 4G. However, 5G NR cannot completely replace 4G Long Term Evolution, and 5G will not change the telecommunication field in the near future [6]. In the next decade, 4G will still coexist with 5G for a long time to provide a relatively seamless user experience [7]. The long-term coexistence of 4G/5G will make it difficult for 5G to directly refarm these low-frequency resources. However, a high-frequency deployment of NR will lead to weak coverage of a single station, and it is difficult to achieve a continuous 5G coverage network in a short time [8,9]. High-frequency signal penetration is weak, even in dense urban areas, signals have the difficulty to penetrate indoor scenes. The development of NR at low frequencies has been the focus of research [10].

Secondly, 4G evolves stably to 5G: When NR is deployed, operators can divide 4G low-frequency resources and give a fixed bandwidth. It cooperates with the high frequency regime to build 5G after refarming, that is, the carrier aggregation (CA). The CA was studied in [11–14]. This scheme has separate dedicated spectrum resources for LTE and NR, deployed as neighbors on the same low-frequency band [15]. However, this hard-partitioning approach will reduce the available 4G spectrum resource, leading to 4G network congestion and the risk of degraded 4G user experience. In the early stages of 5G deployment, terminal penetration and lack of users, and 5G deployment in reserved dedicated carriers may result in an inefficient spectrum. How to dynamically adjust the frequency resource allocation according to the service volume to ensure stable evolution from 4G to 5G is an urgent issue to be solved [16].

Dynamic spectrum sharing (DSS) can effectively solve the above problems. 4G/5G dynamic sharing allows LTE and NR to work on the same band and share frequency resources dynamically between LTE and NR according to the service ratio [17]. DSS realizes the decoupling of the system and spectrum. The same spectrum can be scheduled by multiple systems at the same time, which improves the efficiency of spectrum use and reduces the risk of shifting the LTE frequency in the early stage of 5G broadband construction. While sharing the spectrum between 4G and 5G systems via DSS would result in wasted resources, DSS is an effective and feasible transition method to address the growing high data rate and capacity needs of mobile network operators (MNOs) [18]. This paper is based on the DSS technology, which is a reference for the rapid development of global 5G networks and vertical industries.

From a technical point of view, 4G/5G allows dynamic spectrum sharing mainly because the NR protocol design originates from LTE, which has a high degree of inheritance and similarity. The third generation partnership project (3GPP) fully considered the need for dynamic sharing of NR and LTE spectrum at the beginning of the Release 15 NR system design. Many designs of NR use the same or extended parameters as LTE so that the two systems have the basis for coexistence. Uplink alignment of LTE and NR is specified in [19] for orthogonality and radio bearer (RB) avoidance. Meanwhile, the 3GPP protocol introduces rate matching [20,21], which further guarantees the reliability of dynamically sharing networks between 5G and 4G.

Existing research on spectrum sharing has focused on novel network architectures, physical layers, and high-level issues in spectrum resource management and regulation. Reference [22] provides a comprehensive summary of crucial future DSS trends, regulatory reform initiatives, and research challenges; references [23,24] focus on the management of spectrum sharing; references [25–28] study the improvement of the spectrum sharing technique; references [29,30] focus on the service level of spectrum sharing.

DSS is able to low-frequency overlapping deployments of LTE and NR, but the problem of intra-frequency interference in inter-system networks cannot be ignored. Interference has always been a key concern of NR networks. Reference [31] focuses on time division duplexing (TDD) cross-link interference; references [32,33] focus on interference coordination; references [34,35] focus on interference management. In 4G and 5G dynamic spectrum sharing, the physical layer share channels carrying user-plane services can be flexibly scheduled to achieve time division or frequency division multiplexing of spectrum resources, without generating 4G and 5G interference conflicts. However, the physical layer control channel cannot be flexibly scheduled and needs to be statically configured to avoid interference. The allocation method of the time-frequency resources of the physical layer is the key to solving the conflict of the control channel in the dynamic spectrum sharing [36]. Compared with 4G, 5G physical layer control channel configuration is more flexible. It is possible to avoid interference conflicts by configuring the physical layer control channel of the 5G network. However, there are few studies on the interference principles and corresponding solutions for 4G and 5G DSS.

Related Work

In this section, we compare some existing literature related to DSS interference. The authors of [37] proposed a zero-breaking beamforming approach for interference cancellation in a cognitive radio. However, these authors focused their research on the channel estimation problem that accompanies the adoption of the zero-breaking beamforming approach. This reference only mentions the idea of dynamic spectrum access as a candidate solution and does not provide an in-depth analysis, and the proposed interference solution does not explicitly target the DSS interference scenario. Reference [38] has a similar research direction as [37], which is also based on dynamic spectrum access for a cognitive radio. The authors of [38] proposed three solutions for mobile spectrum shortage, namely, interleaved CR, underlay CR, and overlay CR. The interference mitigation methods are proposed are not for 4/5G DSS interference scenarios and without field test. In our paper, compared with these two literature references, we focus on the 4/5G interference in DSS scenarios, and propose two interference mitigation methods, namely, rate matching and buffer setting, to mitigate the interference. We add a large number of field tests based on simulation which can verify our proposed methods more comprehensively. The authors of [39] proposed an adaptive system model of downlink interference for 5G mobile communication applications. The interference impact of the downlink 5G system was measured with two different mobile terminals: MediaTek (MTK) and Qualcomm (QC). That is, the existence of interference was determined by field verification, but no effective solution for interference mitigation was proposed, simulated and measured. Our paper proposes two interference mitigation solutions for the severe interference found in the DSS, which is the core research point of our paper. We further conduct an in-depth study and analysis of the feasibility and effectiveness of these two interference mitigation solutions by conducting simulations and field tests. The research background of references [36,40] is also similar to the research conducted in this paper. Therefore, we have a foundation for our paper. However, the authors of [36,40] only compared the performance of several modes at 20 MHz bandwidth. The presence of interference was determined by field verification, but no interference mitigation scheme was proposed, simulated, and measured. On the other hand, our paper carries out many extended studies based on references [36,40]. We further realize the prospective study of references [36,40] by conducting research and analysis in a larger bandwidth scenario, and further propose two interference mitigation solutions for the severe interference in the DSS. Our paper presents simulations and field tests on the feasibility and effectiveness of these two solutions. An in-depth study and analysis is conducted based on the previous work, and the interference problems found in the previous work are effectively solved.

The remainder of the paper is organized as follows. Section 2 introduces the motivation and contribution of this paper. Section 3 investigates the technical solution of the DSS. In Section 4, the principle of intra-frequency interference under the DSS network architecture and two interference mitigation solutions of rate matching and buffer setting are presented. Section 5 provides the field test results and analysis of interference, and verification of buffer setting and rate matching solutions. Section 6 summarizes the conclusion.

2. Motivation and Contribution

Facing the long-term coexistence of 4G and 5G, DSS technology can dynamically share the spectrum between 4G and 5G as an effective transition solution, offering the possibility of stable evolution from 4G to 5G. However, DSS will introduce intra-frequency interference between inter-systems in the network, which seriously affects the user experience.

The main contributions of this paper are summarized as follows:

- The interference between 4G and 5G DSS was not addressed, and they have not been tested and validated in commercial networks.
- We have innovatively proposed two interference solutions: buffer setting and rate matching, and performed a theoretical analysis and field validation for the first time in

a real commercial 4G/5G coexistence network built based on mainstream equipment vendors.

- The analysis and evaluation of the interference situation and the performance improvement after taking the proposed scheme are provided based on the real-time network performance and the target user experience. This is also the first study in the world to share the 4G/5G DSS interference solution, which is analyzed and verified from both theoretical and experimental perspectives.

3. Dynamic Spectrum Sharing

DSS supports LTE and NR to jointly use the uplink and downlink spectrum resources of the same band. When there is no independent NR spectrum resource, the spectrum can be shared with the existing LTE to obtain the ability to rapidly deploy 5G networks. When independent NR spectrum resources are available, they can be also shared with LTE to improve spectrum utilization. The DSS architecture is shown in Figure 1, where the evolved packet core (EPC) is the 4G core network, the 5G core (5GC) is the 5G core network, the evolved node B (eNodeB) is the 4G base station, the next-generation node B (gNodeB) is the 5G base station, and UE is the user equipment. The eNodeB and the gNodeB are one base station physically, but two base stations logically.

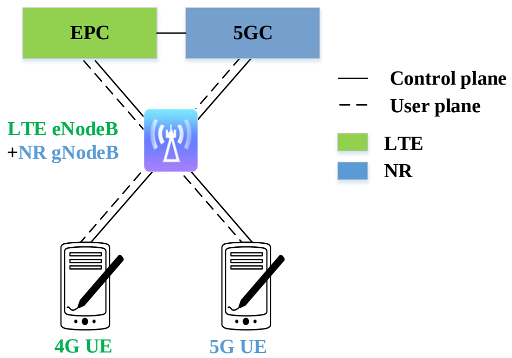

Figure 1. DSS architecture.

DSS adopts a flexible scheduling algorithm: LTE and NR service requests are judged with the accuracy of transmission time interval (TTI). The available frequency-domain resources are dynamically allocated based on the service application volume of LTE and NR according to the allocation algorithm so that spectrum utilization efficiency is maximized, as shown in Figure 2. The minimum scheduling precision in the frequency domain is the RB level, and the minimum scheduling precision in the time domain is the TTI level.

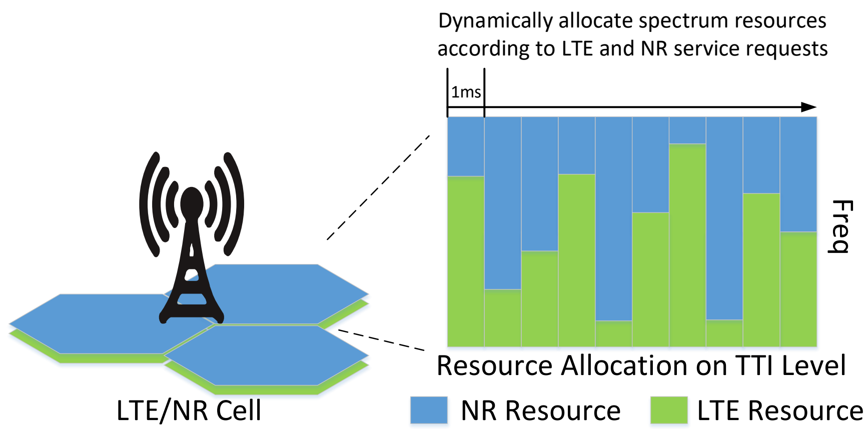

Figure 2. DSS dynamically adjusts spectrum resources.

The basis for DSS between 4G and 5G is that the physical layers of both NR and LTE are designed based on orthogonal frequency division multiplexing (OFDM). Meanwhile, NR can choose the same parameter set as LTE, i.e., the same subcarrier spacing and time slot structure. The NR architecture is fully compatible with LTE and guarantees its independence. The LTE cell reference signal (CRS) and control channels occupy specific positions in continuous time- and frequency-domain resources, while NR reference signals, data channels, and control channels are highly flexible, allowing dynamic configuration. Therefore, using the dynamic flexibility of the NR physical layer to adapt to the relatively fixed LTE can avoid conflicts between the two technologies.

For uplink physical channels, the physical uplink shared channel (PUSCH) of LTE and NR are dynamically shared according to uplink service requests; the physical uplink control channel (PUCCH)/physical random access channel (PRACH)/PUSCH of LTE and NR can avoid each other by means of frequency division multiplexing. The LTE PUCCH occupies 4–6 RBs, and NR PUCCH occupies 8–10 RBs. The PRACH of LTE and NR are periodically sent at fixed positions, each occupying 6 RBs. The LTE PRACH is close to the LTE PUCCH at low frequency; the NR PRACH is close to the LTE PUCCH at high frequency. The uplink channel map is shown in Figure 3.

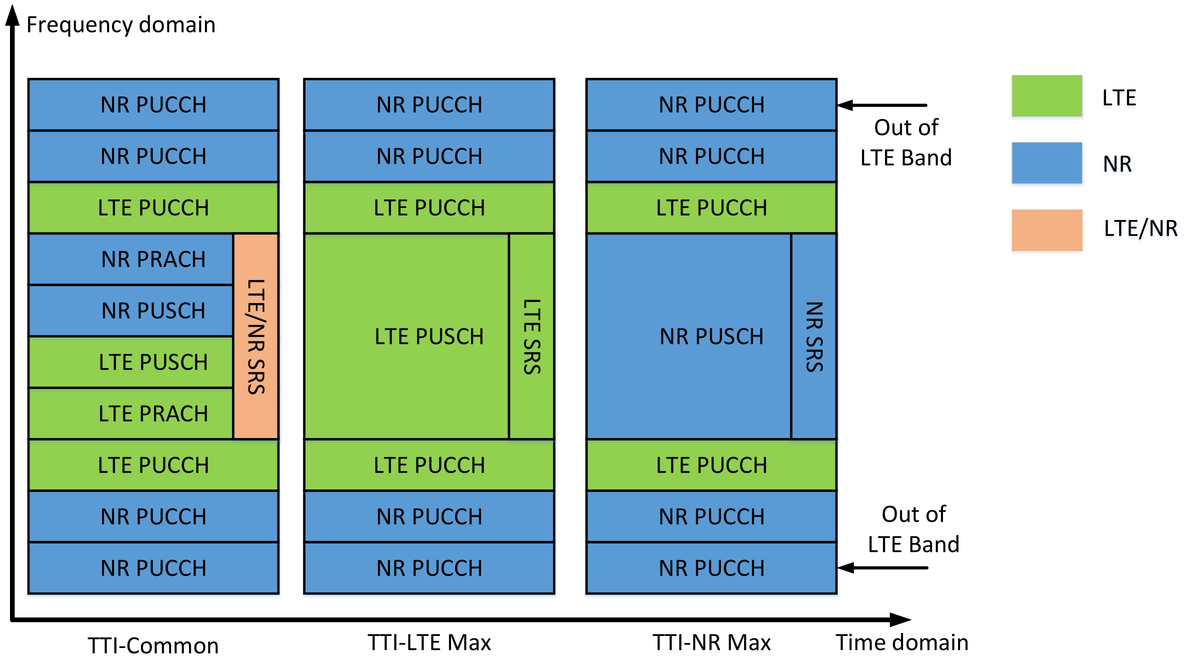

Figure 3. Uplink channel map.

For downlink physical channels, the PDSCH of LTE and NR avoid each other in a frequency-division multiplexing (FDM) manner, where the LTE frequency is allocated from high to low, and NR frequency is allocated from low to high. LTE and NR PDCCH use time-division multiplexing (TDM) to avoid each other, occupy the full bandwidth in the frequency domain, and dynamically occupy the first three symbols of each TTI in the time domain. The resource conflict of single side band (SSB), system information block (SIB), Page, message2 (Msg2), message4 (Msg4), and LTE CRS in NR can be avoided by adopting NR rate matching. The downlink channel map is shown in Figure 4.

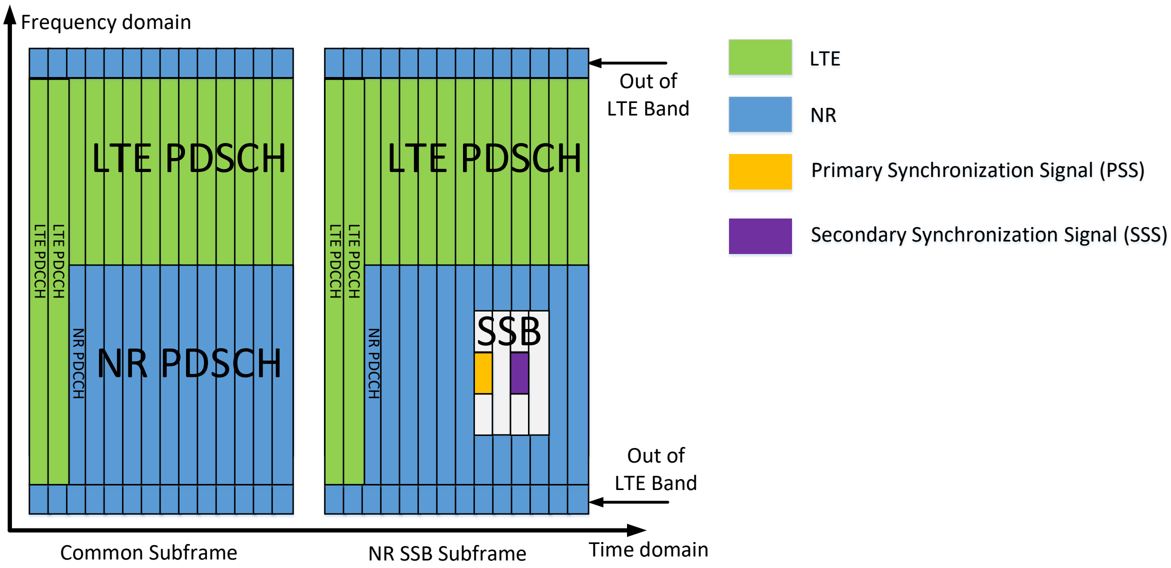

Figure 4. Downlink channel map.

4. DSS Interference and Solutions

As mentioned in the previous section, DSS means that the same time-frequency resources can be dynamically and flexibly provided for inter-system in the same frequency band. The current 4G and 5G frequencies may be refarmed, which may cause intra-frequency interference between networks.

4.1. DSS Interference Principle

DSS is deployed with 4G and 5G spectrum sharing, both LTE and NR are OFDM symbols with LTE subcarrier spacing of 15 kHz and NR low-frequency subcarrier spacing of 30 kHz. The frame length and time slot ratios are kept consistent for both networks, and both time and frequency domains are aligned [41]. However, since 4G is a broadband system, the channel configuration is relatively broad, with full-band mapping of control channels, pilot frequency, etc. 5G is a broadband system with the same types of physical channels. Therefore, the reference signal such as SSB or the demodulation reference signal (DMRS) of 5G NR will conflict with the reference signal (CRS) of LTE in terms of time and frequency resource allocation. It is easy to cause intra-frequency interference between LTE and NR. Due to the flexibility of the NR physical layer, 5G interference is less than 4G, and 4G interference is more than 5G [42].

In addition, there is serious interference in the DSS networking, which has a great impact on the wireless network environment and user experience. LTE is based on physical cell identifier (PCI) Mode 3, which means that there is a mode 3 interference of LTE [43]. The 3GPP protocol stipulates that there are 4 cell common reference signals (CRS) in each RB [44]. In this case, it is specified that there is one CRS in every six subcarriers in the frequency domain and the CRS is located in the first and fifth symbols in the time domain. Since the LTE system uses a dual antenna transceiver, there are three cases of positions of CRS within RB, which are shown in Figure 5A–C.

As shown in Figure 5, if the CRS is in the same position within the RB, this is a mode 3 conflict, also called mode 3 interference. Since there are only three possible positions of CRS within RB, a mode 3 conflict is bound to occur when signals from four or more cells appear at the same position [45].

Figure 6 shows a schematic diagram of DSS interference.

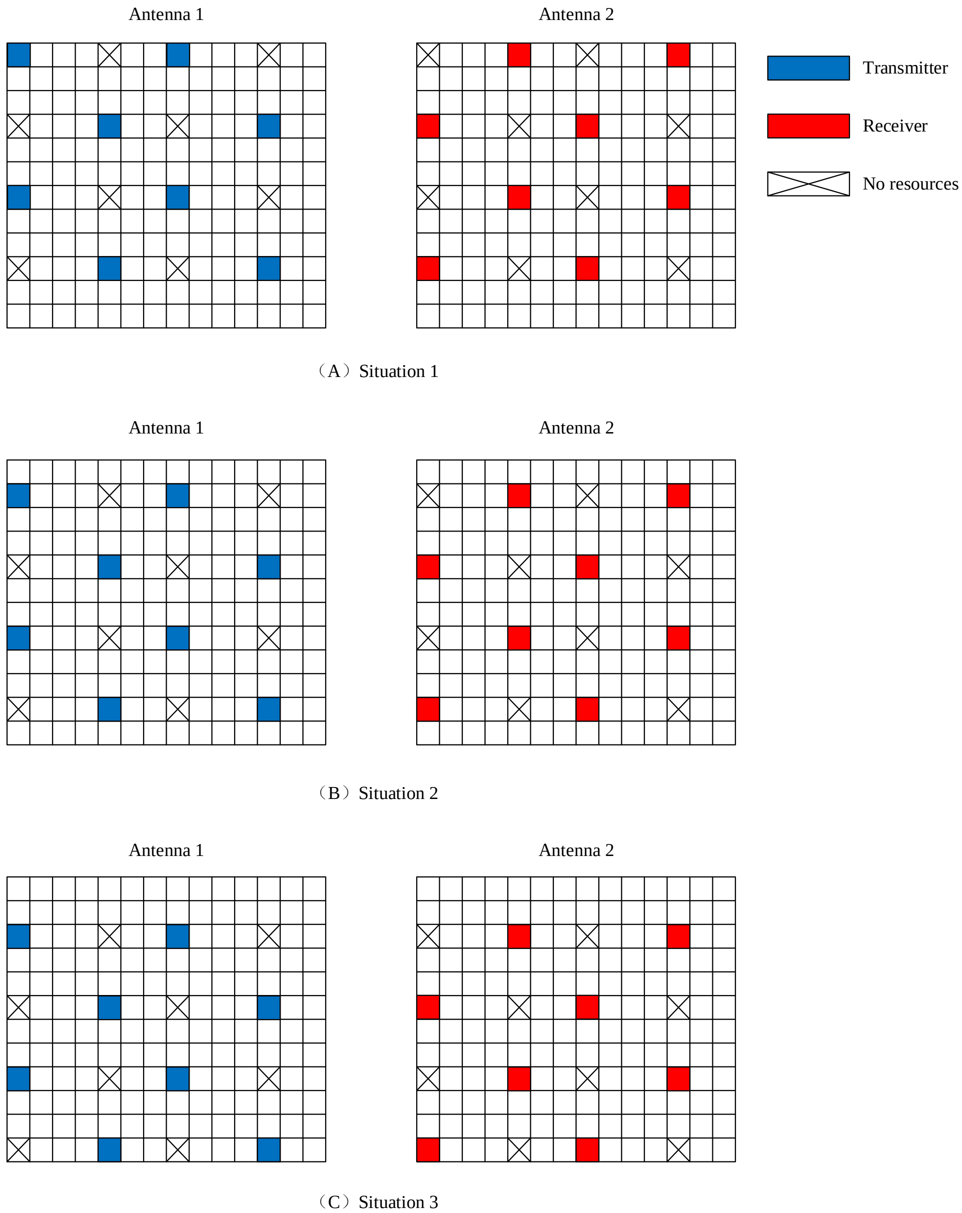

Figure 5. Positions of CRS within RB.

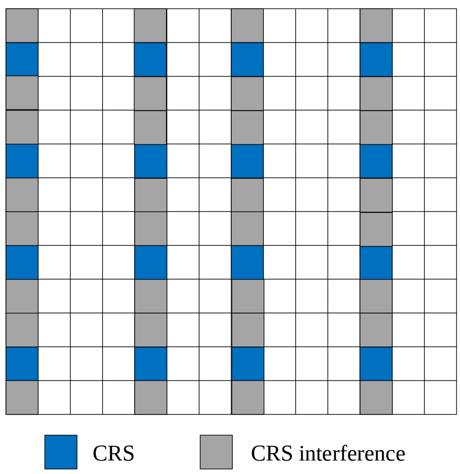

Figure 6. Schematic diagram of DSS interference.

Since LTE CRS always exists and there is no CRS interference cancellation mechanism for NR terminals, LTE based on PCI Mode 3 planning will destroy the demodulation of NR time-frequency resources in the shaded part of the figure, thus bringing interference. This paper mainly analyzes the more serious DSS neighbor interference in the existing network.

4.2. Buffer Setting

For DSS neighbor interference, we can use the common buffer method to solve it, that is, set a buffer. Taking the 2.1 GHz intra-frequency networking environment as an example, the LTE of the DSS cell will cause strong interference to the NR of the neighbor DSS cell. If two circles of disturbing base stations near the disturbed base station are closed, the coverage of the area near the disturbed base station will be discontinuous. Therefore, eNodeBs in a non-2.1 GHz band (e.g., 1.8 GHz) can be considered to replace the base stations that need to be turned off to play the role of a buffer, thereby mitigating the intra-frequency interference in neighbors. The schematic diagram of buffer setting is shown in Figure 7. Points 1 to 6 are the test point in our paper. The darker the color, the stronger the interference.

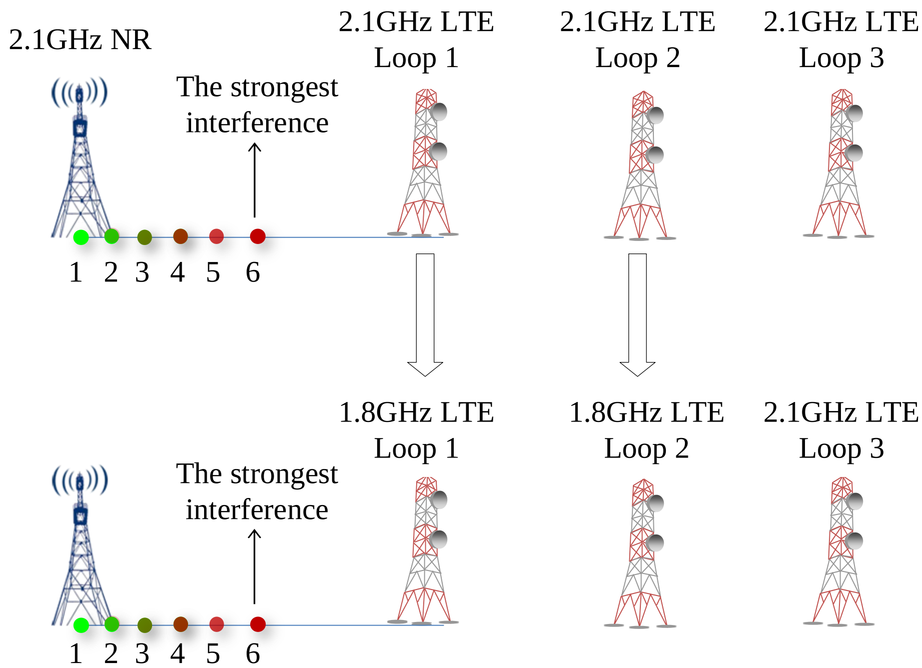

Figure 7. Schematic diagram of the buffer.

We conducted a simulation analysis for a buffer setting solution to mitigate the interference caused by LTE to NR downlink, and the results are shown in Figure 8.

As can be seen from Figure 8, when the isolation of LTE increases, the rate of NR is getting higher and higher, indicating that the buffer has a significant mitigation effect on interference. When the LTE isolation is 15 dB, the downlink performance of NR can reach up to 32 Mbps. Compared with without buffer, the downlink performance of NR can be improved by 40–60%. Therefore, if the downlink interference level of LTE to NR is reduced, it is better to set the isolation of LTE to 15 dB or more. Considering the irregularity of the field network, it can be increased by 5 dB, that is, the isolation of 20 dB can be set, which is equivalent to the situation of closing two base stations in the field network.

In Section 5, we conduct a field test analysis to verify the conclusions of the theoretical analysis of the interference mitigation effect produced by buffer setting.

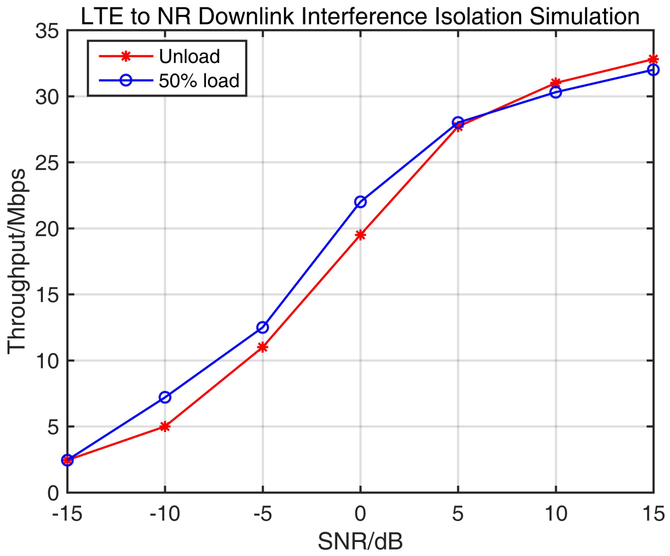

Figure 8. Simulation results of buffer setting.

4.3. Rate Matching

In order to dynamically share time-frequency resources with LTE networks, 5G supports two rate-matching schemes, RB-level and resource element (RE)-level. These two schemes are commonly used in NR data channels so that the NR scheduler can identify which REs are not available for data scheduling on the PDSCH [36]. In this paper, we use the RE-level rate matching scheme, which includes LTE CRS and ZP channel state information-reference signal (CSI-RS). LTE CRS matching is mainly used in 5G and 4G DSS.

According to the 3GPP protocol, LTE CRS rate matching is a function that must be supported by 5G terminals. 5G terminals need to report the support capability of LTE CRS rate matching according to the frequency band. LTE CRS rate matching allows NR not to send NR PDSCH on REs occupied by LTE CRS. When the 5G terminal demodulates the PDSCH, the terminal will skip the REs occupied by the LTE CRS [46].

LTE CRS matching is configured via the lte-CRS-ToMatchAround parameter in ServingCellConfig or ServingCellConfigCommon. The time-frequency position of the CRS in the LTE network is determined by the PCI and the number of antenna ports. The PCI determines the v-Shift during the CRS physical resource map. Therefore, when LTE CRS matching is configured in the 5G network, the lte-CRS-ToMatchAround needs to carry v-Shift and nrofCRS-Ports (number of antenna ports). Since the LTE bandwidth is part of the 5G bandwidth, when LTE CRS is matched, the center frequency and width of the LTE frequency bandwidth need to be configured through carrierFreqDL and carrierBandwidthDL. The CRS physical resource map method of the multicast broadcast single frequency network (MBSFN) subframe of the LTE network is inconsistent with that of the common subframe. Therefore, if the subframe of the LTE network is an MBSFN, the lte-CRS-ToMatchAround also needs to carry the configuration of the MBSFN. LTE PDCCH is configured with 1 symbol, NR PDCCH is configured with 2 symbols in the time domain and 24 RBs in the frequency domain, using interleaving mapping with interleaving length (R) and resource element group (REG) binding length (L) configured as 2. The method of interleaving mapping is as follows.

The REG is first bound and L is defined as the binding length of the REG. The REG bundle is configured by the high-level parameter reg-BundleSize, and i is defined as REGs, as shown in Equation (1).

$$i = 0, 1, \ldots, N_{REG}^{CORESET}/L - 1 \quad (1)$$

The number of *REG*s in *CORESET* is equal to the number of *RB*s in *CORESET* plus the number of symbols in *CORESET*, as shown in Equation (2).

$$N_{REG}^{CORESET} = N_{RB}^{CORESET} + N_{symb}^{CORESET} \tag{2}$$

CCE j is composed of *REG* bundles $\{f(6j/L), f(6j/L+1), \ldots, f(6j/L+6/L-1)\}$, where $f(x)$ is the interleaver. CCE means Cooperative Computing Environment.

When using interleaving mapping, when $N_{symb}^{CORESET} = 1, L \in \{2,6\}$. When $N_{symb}^{CORESET} \in \{2,3\}, L \in \{N_{symb}^{CORESET}, 6\}$. This design ensures that $N_{RB}^{CORESET}/L$ is an integer. In this way, all *REG*s can be fully used when binding.

Further, Equations (3) to (7) can be adopted for interleaving.

$$f(x) = (rC + c + n_{shift}) mod (N_{REG}^{CORESET}/L) \tag{3}$$

$$x = cR + r \tag{4}$$

$$r = 0, 1, \ldots, R-1 \tag{5}$$

$$c = 0, 1, \ldots, C-1 \tag{6}$$

$$C = N_{REG}^{CORESET}/(LR) \tag{7}$$

R is the length of the interleaver, which can be configured as 2, 3, or 6. It can be configured through the high-level parameter interleaver size. $n_{shift} \in \{0, 1, \ldots, 274\}$ can be configured through the high-level parameter shift Index. If the upper layer is not configured, then $n_{shift} = N_{ID}^{cell}$. C must be an integer. Thereby, the interleaving mapping can be completed.

In addition, LTE needs to reserve 24 *RB*s for NR to send SSB and remaining minimum system information (RMSI) every 20 ms. When NR sends SSB and RMSI, LTE does not send CRS within the SSB/RMSI region [21,47,48]. Figure 9 shows a schematic of rate matching.

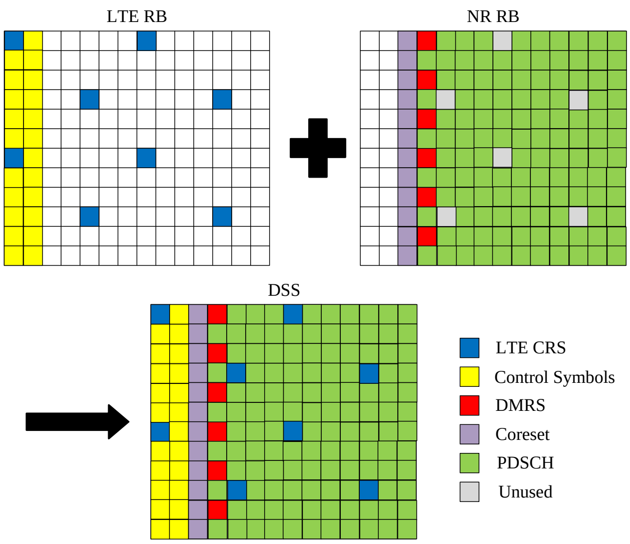

Figure 9. Schematic diagram of rate matching.

Through theoretical analysis, it is known that DSS cells will cause inter-standard interference due to resource conflict, which needs to be avoided by rate matching. At the same time, the interference of the DSS cell by the neighbor base station can also be solved by rate matching.

We simulated and analyzed the interference caused by the LTE to NR downlink caused by the rate matching scheme, and the results are shown in Figure 10.

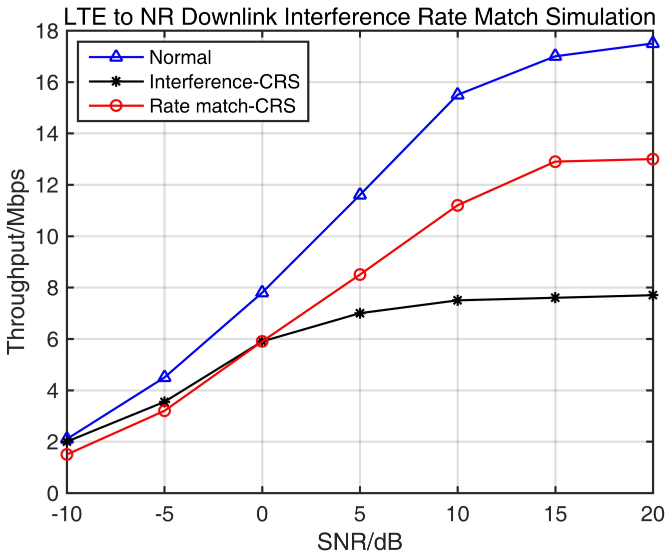

Figure 10. Simulation of rate matching.

In Figure 10, Normal is the throughput when NR is not interfered, Interference-CRS is the throughput when NR is interfered by LTE CRS, and Rate match-CRS is the throughput after rate matching is used when NR is interfered. It is obvious that when NR is interfered by LTE-CRS, its throughput will be reduced up to 56%, which shows that the interference of LTE to NR is very serious. After the CRS rate-matching scheme is adopted, the rate of NR will be reduced by about 25% compared with that without interference, but the throughput of NR will be increased by about 60% when it is interfered. It can be seen that although the rate-matching scheme will bring a certain amount of resource overhead, it can ensure that the NR throughput will not drop significantly when the interference is heavy, and ensure the user's network experience, which is an effective interference mitigation solution.

We compared the two schemes of rate matching and buffer setting, and the simulation results are shown in Figure 11.

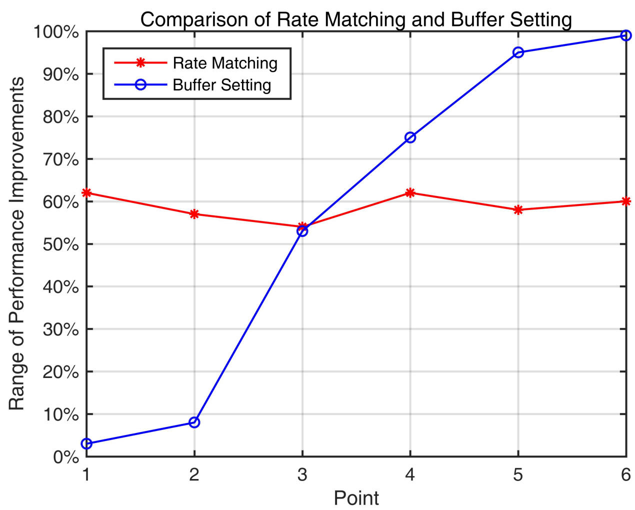

Figure 11. Simulation of rate matching.

It can be seen in Figure 11 that the effects of the buffer setting solution and the rate matching solution are different. The performance improvement effect of the buffer setting solution is inconsistent at each point: the farther the distance from the observed base station, the better the interference mitigation effect, up to 99%. The closer the distance, the less the improvement effect, down to 3%. Instead, the rate-matching solution can steadily improve the interference mitigation performance at all locations, about 60%.

In summary, both the rate-matching scheme and the buffer setting scheme can theoretically reduce the neighbor interference. However, the effectiveness of the theoretical analysis and the advantages and disadvantages of the two solutions need to be verified by field tests.

5. Field Test and Performance Analysis

5.1. Test Environment

The data to be analyzed in this chapter are processed from field measurements with large sample sizes. The test analysis introduced in this chapter is mainly to test the DSS cell that is interfered by neighbor cells.

This performance test was conducted in a commercial LTE/NR network. The test area includes residential buildings, small commercial streets, and schools, which are typical test scenarios. The test area is a multi-cell networking scenario with small station spacing and coverage overlap between the test cell and neighbor cells. We respectively verified the effect DSS neighbor cells have on LTE and NR of DSS test cells for no-load and 50% loading cases.

The modulation in this test is 256QAM, the antenna height is 35 m, the bandwidth is 40 MHz, the subcarrier interval is 15 kHz, and the frame structure is in FDD mode.

The test environment is shown in Figures 12 and 13.

Figure 12. Test environment.

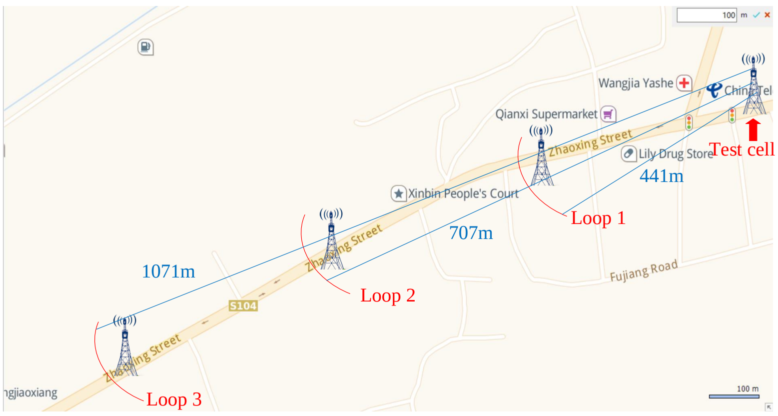

Figure 13. Test environment networking diagram.

The distances of the six test points from the test cell are shown in Table 1.

Table 1. Distance of The Six Test Points From The Test Cell.

Test Point	1	2	3	4	5	6
Distance (m)	51	90	142	200	248	288

The on and off of the test base station are shown in Table 2.

Table 2. Test Base Station On/Off.

Neighbor Cell Status	Loop 1: Xinbin Life Insurance Community	Loop 2: Xinbin Procuratorate	Loop 3: Xinbin Urban Development Bureau
On	On	On	On
1 loop off	Off	On	On
2 loops off	Off	Off	On

The specific data analysis of the test is performed below.

5.2. Neighbor Cell Interference Test

During the downlink test, all base stations turn on, and the neighbor cell base stations are Xinbin Life Cell, Xinbin Procuratorate, and Xinbin Urban Development Bureau in Table 1, configured as NR Only or LTE Only. We perform downlink ping tests at six test points, respectively, to observe the downlink throughput.

5.2.1. NR Downlink Interference from LTE of Neighbor Cells to DSS Test Cells

The test results are shown in Figure 14.

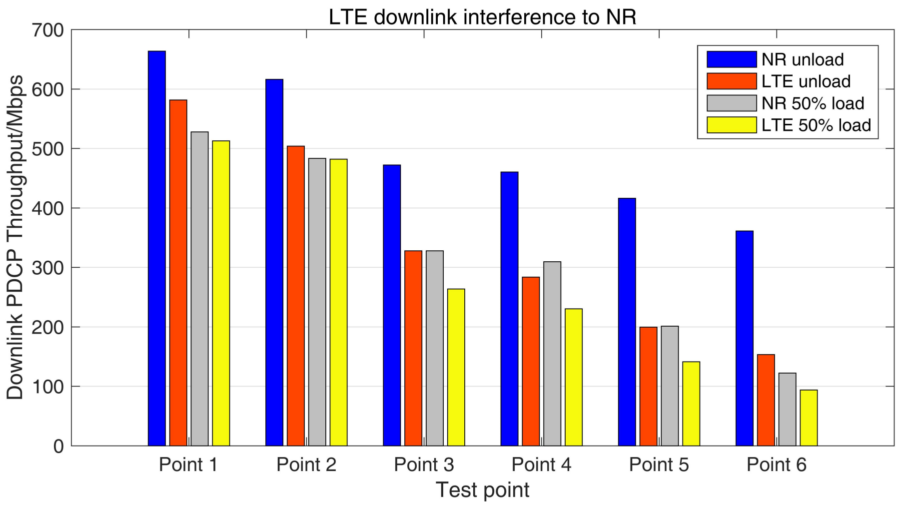

Figure 14. LTE to NR downlink interference test results.

As can be seen in Figure 14, the downlink throughput decreases with increasing distance. When the neighbor cell is changed from NR Only to LTE Only, the downlink throughput is greatly reduced, and the throughput dropped by 57% at point 6 with the strongest interference. In the case of no-load, compared with NR, the LTE of neighbor cells will reduce the NR downlink performance of the DSS test cell by about 34% on average. With 50% load, LTE degrades the NR downlink performance of the DSS test cell by about 15%. It can be seen that the interference brought by LTE has a great influence and cannot be ignored.

5.2.2. LTE Downlink Interference from NR of Adjacent Cells to DSS Test Cells

The test results are shown in Figure 15.

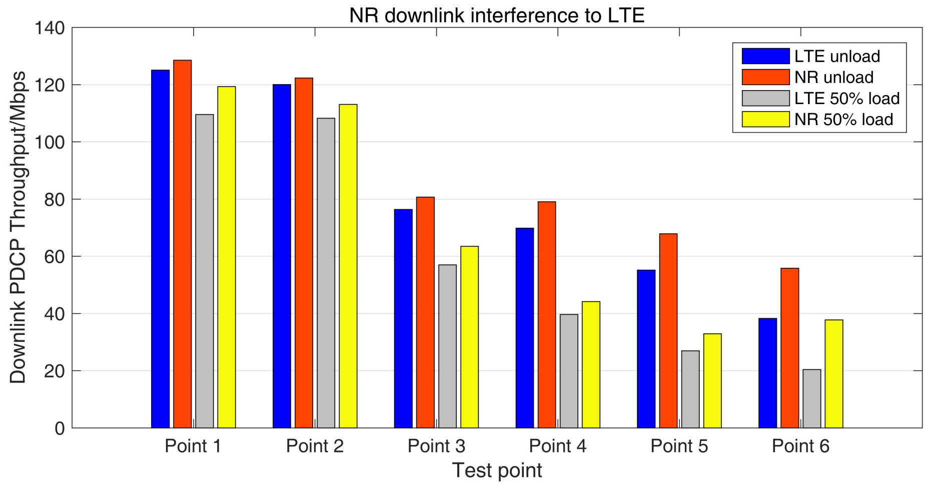

Figure 15. NR to LTE downlink interference test results.

As can be seen in Figure 15, compared to LTE neighbor cells, NR neighbor cells not only do not affect LTE cell downlink performance but also improve LTE cell downlink performance. Regardless of whether it is no-load or 50% load, the NR of neighbor cells will increase the LTE downlink performance of the DSS test cell by about 11% on average, and the throughput can be recovered by 45% at the furthest point with the strongest interference. This is mainly because NR does not need to continuously send full bandwidth CRS, so NR in DSS neighbor cells does not cause downlink interference to LTE in DSS test cells.

During the uplink test, all test base stations turn on, and the test cell base stations are Xinbin Life Cell, Xinbin Procuratorate, and Xinbin Urban Development Bureau in Table 1, configured as NR Only or LTE Only. We perform uplink packet filling tests at six test points to observe the uplink throughput.

5.2.3. LTE Uplink Interference From NR Terminal to DSS Cells

At the same point, use the NR and LTE test terminals to perform uplink ping, respectively, and observe the background noise. When there are no terminal upload data, the LTE background noise of the tested DSS cell is −120 dB. When NR and LTE terminals upload data, the test results are shown in Figure 16.

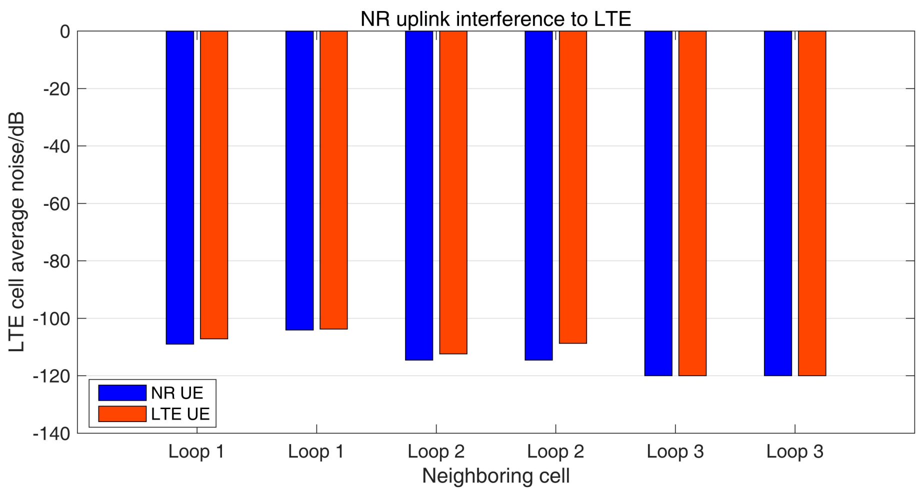

Figure 16. NR terminal to LTE uplink interference test results.

As can be seen from Figure 16, the impact of the NR terminal on the LTE background noise increase in the first circle neighbor DSS cell is basically the same as that of the LTE terminal, and the difference in the background noise increase is about 1.11 dB. In the first circle of DSS cells, the LTE uplink background noise increased by about 10%. The impact of the NR terminal on the LTE background noise increase in the second circle neighbor DSS cell is basically the same as that of the LTE terminal, and the difference in the background noise increase is about 3.95 dB. In the second circle of DSS cells, the LTE uplink background noise increased by about 10%. The terminal has no effect on the rise of the background noise of the third circle. It can be seen that the LTE uplink interference from the NR terminal to the DSS cell can be neglected compared to the NR downlink interference from the LTE to the DSS test cell in the neighbor cell.

5.2.4. NR Uplink Interference of LTE Terminal to DSS Cell

The test results are shown in Figure 17.

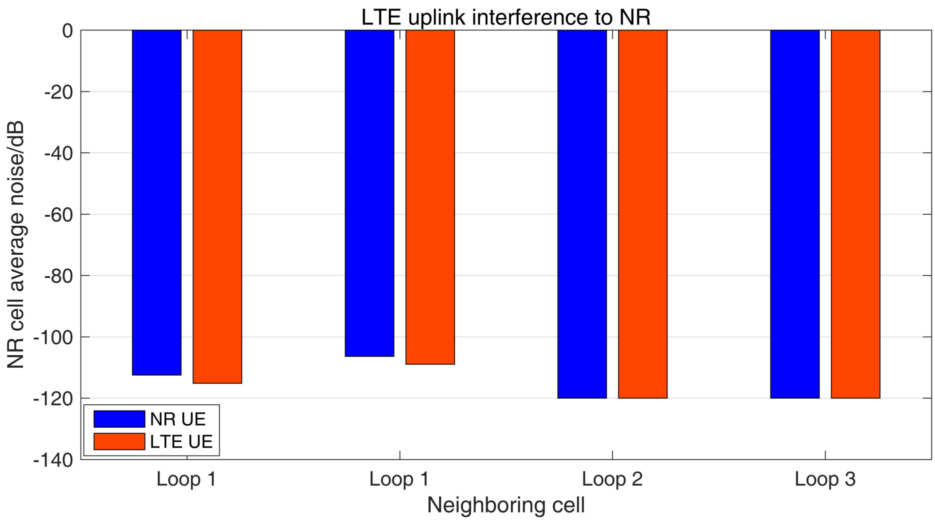

Figure 17. LTE terminal to NR uplink interference test results.

As can be seen from Figure 17, the impact of the LTE terminal on the raised background noise of the first circle DSS NR cell is basically the same as that of the NR terminal, and the difference in raised background noise is about 2.66 dB. In the first circle of DSS cell, the uplink background noise of the NR cell is raised by about 7%. The terminal has no effect on the background noise increase of the NR cell in the second and third rounds of DSS. It can be seen that the NR uplink interference from LTE terminals to DSS cells can be neglected.

Through the analysis of the above test results, we can find that in the DSS networking scenario, LTE in DSS cells will not be affected by NR in neighbor DSS cells, and there is also no significant interference from LTE and NR terminals to NR and LTE in DSS cells, respectively. However, the NR of the DSS cell will be strongly interfered by the LTE of the neighbor DSS cell, which will seriously affect the user experience. Therefore, it is necessary to take interference mitigation solutions to improve network performance.

5.3. Test Results for Buffer Setting

As can be seen through Section 5.2, only LTE has a more serious downlink impact on NR and therefore requires interference mitigation solutions. In Section 4.2, we propose the solution of buffer setting to solve the interference problem. In this section, we verify the feasibility by field tests.

We verified the LTE interference to the NR of DSS test cell when one and two circles of base stations were turned off, respectively, and the test results are shown in Figures 18 and 19.

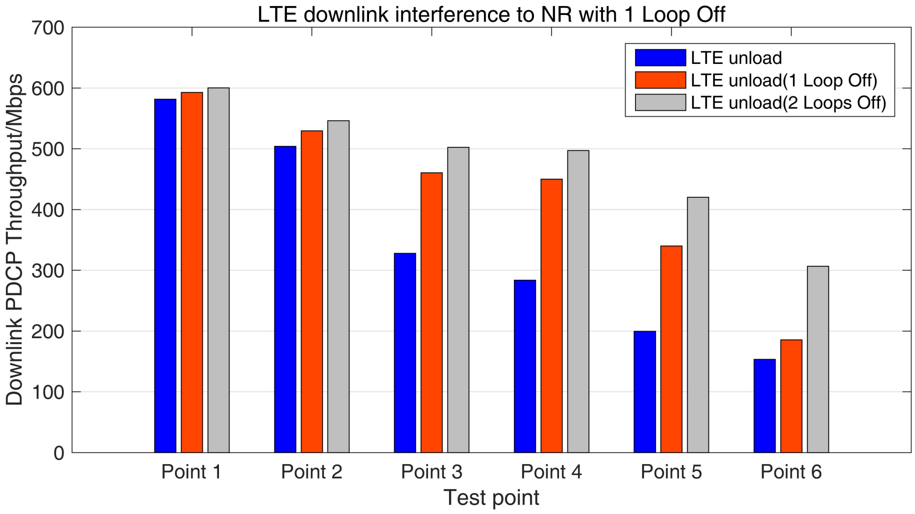

Figure 18. LTE to NR downlink interference test results—buffer setting (no load).

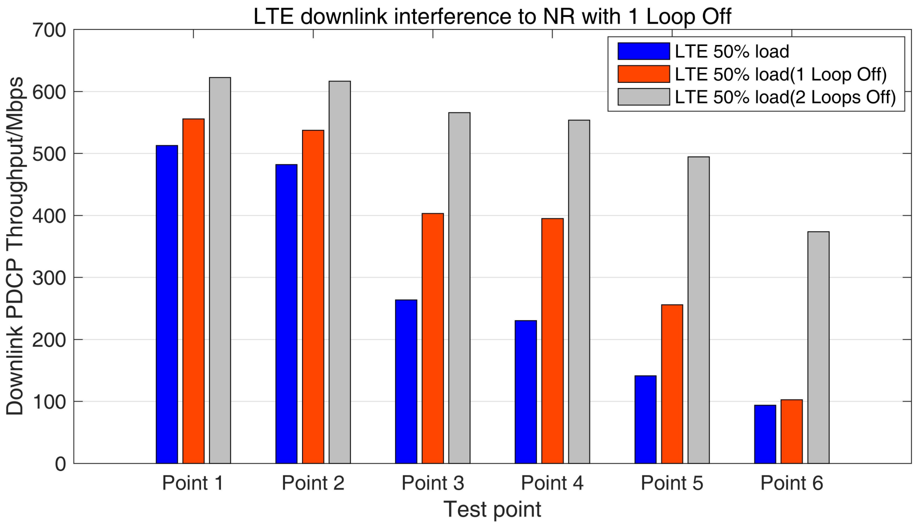

Figure 19. LTE to NR downlink interference test results—buffer setting (50% load).

As can be seen in Figures 18 and 19, whether it is no load or 50% load, closing one circle of interfering cells can effectively improve the NR throughput of the test cell, with an average of about 30%. Closing two circles of interfering cells can greatly improve the throughput of the test cells, by an average of about 60%, and at test point 6, it can be increased by up to 99%. The closer the distance to the interfering cell is, the more obvious the bit rate improvement effect. The test results are consistent with the theoretical analysis results in Section 4.2.

It can be learned that setting the buffer between DSS cells can effectively reduce downlink interference from LTE cells to neighbor NR cells and improve user experience. However, the impact of setting the buffer on the six test points varies greatly and is not stable. Therefore, we further test and verify the rate-matching scheme.

5.4. Test Results of Rate Matching

Since the LTE of the DSS cell will cause serious interference to the NR of the DSS neighbor cells, we verify the interference mitigation after rate matching. The test environment is shown in Figure 13, and the no-load and 50% load conditions are verified, respectively, and the base stations are all turned on. The test results are shown in Figure 20.

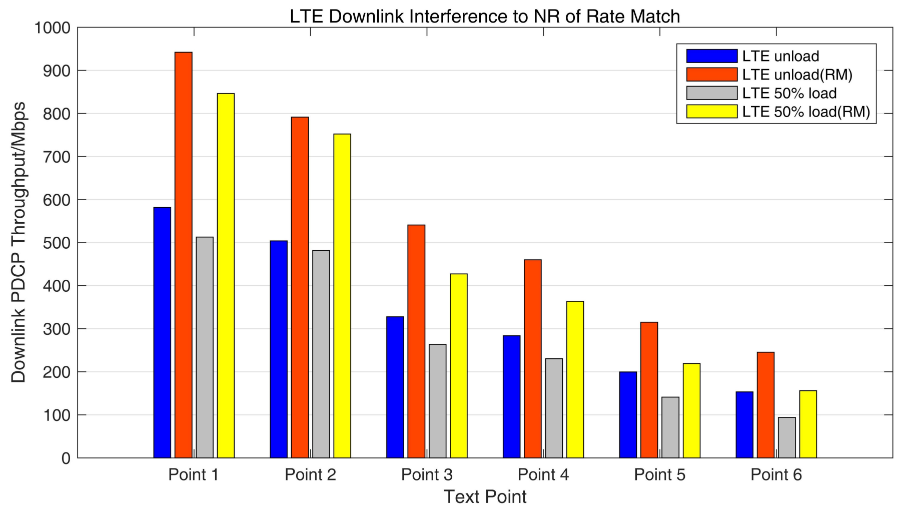

Figure 20. LTE to NR Downlink Interference Test Results after Rate Matching.

As can be seen in Figure 20, regardless of whether it is no-load or 50% load, with rate matching, the LTE interference to NR in the neighbor DSS is significantly reduced. The downlink throughput of NR can be improved by about 60% at different points. It can be seen that the rate-matching scheme can significantly improve the user's network experience without setting the buffers. Therefore, in the case of severe interference, choosing the rate-matching scheme can steadily increase the throughput and mitigate the interference. The test results are consistent with the theoretical analysis results in Section 4.3.

In summary, both the buffer setting scheme and rate matching can effectively mitigate interference, but the buffer setting scheme has a large difference in performance improvement at different locations and lacks stability. The rate-matching scheme can steadily improve the performance of different locations by 60%, and the improvement effect is obvious, which is consistent with the theoretical analysis results. Although rate matching will bring a certain amount of resource overhead, the benefits in interference mitigation are significant, which can effectively and stably improve the user experience.

6. Discussion

In this paper, all results are based on commercially available DSS networks. First, we study the basic architecture of DSS. Then, the theoretical analysis of DSS interference is carried out, and two achievable interference mitigation solutions are innovatively proposed: buffer setting and rate matching. Through theoretical analysis, we found that the NR of the DSS cell will be seriously interfered by the LTE of neighbor DSS, and its performance will be reduced by up to 56%. Setting the buffer can improve the downlink performance of NR of DSS cell by 40–60%; after adopting the CRS rate-matching solution, the downlink performance of NR can be increased by about 60%.

The realistic test environment for this study was built for the first time on a commercial 4G/5G coexistence network, which is unprecedented for DSS interference analysis. Compared with the interference between other inter-systems, most of NR of the DSS cell is strongly interfered by the LTE signal of the neighbor DSS cell. To address this issue, we conducted field tests of buffer setting and rate matching. It has been verified that the buffer setting solution and the rate-matching solution can effectively reduce the intra-frequency interference between the inter-system. The buffer setting solution can improve the performance of the interfered cell by an average of 60%, but down to 10%. Therefore, the performance improvement of this solution is not stable. The rate-matching solution can also improve the performance of the interfered cell by an average of 60%. This is consistent with the conclusion of the theoretical analysis.

From theoretical and practical analysis, it can be verified that the buffer setting solution can effectively mitigate interference, improve network speed, and be deployed easily.

However, unstable performance improvement and network instability may occur. The rate-matching solution can stably increase the network rate by about 60%. The improvement effect is obvious. However, it will bring a certain resource overhead, and there is a risk that the software upgrade will be relatively slow. The operators can choose a solution on demand based on existing networks.

Although we selected commercial test scenarios, we lack traversing all scenarios of loads and user behaviors, and the test environment and scenarios are relatively simple; so, research in this paper is not complete and we can further improve and continue our research. The future work includes studying DSS to integrate more network frequency bands, such as satellite, millimeter wave, etc. Meanwhile, since the implementation of DSS triggers resource wastage, further attempts can be made in the future on how to save spectrum resources. Further, we will consider the DSS interference in inter-systems, and consider integrating AI algorithms and SDN architecture on the basis of DSS to improve network quality more intelligently.

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