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A 5G Coverage Calculation Optimization Algorithm Based on Multifrequency Collaboration

Xiao Li, Han Guo *, Weiliang Xie and Xue Ding

Mobile and Terminal Technology Research Department, China Telecom Research Institute, Beijing 102209, China
* Correspondence: guoh6@chinatelecom.cn

Abstract: The fifth–generation (5G) network is developing rapidly. The network coverage directly influences the quality of service (QoS) of vertical industries. Coverage capability is a crucial and indispensable indicator when evaluating the performance of a network. However, the results of the current algorithm fall short in terms of accuracy. To restore the current status of 5G network coverage more realistically, in this study, we design a new optimization algorithm for coverage calculation based on the traditional coverage algorithm combined with fourth–generation (4G) coverage reference signal receiving power (RSRP) in management report (MR) and adopt a multisystem collaborative analysis method. The algorithm corrects the coverage results and restores the true value of 5G coverage. Based on this, we provide a practical analysis of the largest standalone (SA) commercial network in the world, which confirms the viability of the algorithm. Both theoretical and practical analyses show that the algorithm can effectively detect hidden weak coverage areas, providing a further reference for future 5G construction and improving the 5G user experience. The proposed approach can be broadly generalized and applied to multifrequency, multioperator, or even sixth–generation (6G) networks.

Keywords: coverage algorithm; multifrequency collaboration; 4G; 5G; MR

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1. Introduction

With the continuous increase in the amount of data and the number of devices on wireless networks, the fifth generation (5G) of mobile cellular communication and networking is an important way to meet the demands of users for quality of service (QoS) [1]. Despite capacity and data rates being the main topics under discussion when envisioning 5G mobile communications and beyond, network coverage remains an unavoidable issue, since coverage quality has a significant impact on system performance and user experience [2,3]. On the other hand, the study of coverage in a region or country can also help in estimating the population dynamics [4], as well as provide useful insight concerning human mobility laws [5], natural disaster recovery, urban growth forecasting [6,7], and social graphs. Several studies have reviewed coverage data measurements, reporting analyses in various fields, such as social networks, mobility, geography, security, and business applications [8–10]. Nevertheless, the aforementioned studies hold little significance for further analysis if an accurate assessment of the actual coverage situation cannot be obtained. Therefore, the detection and calculation of the actual 5G coverage situation is crucial.

Compared to the fourth generation (4G), the coverage area of base stations is decreasing while the bandwidth of 5G is increasing [11]. As a result, when user equipment (UE) moves to the boundary of the 5G coverage area, coverage-based handover or redirection becomes necessary so that the 5G UE can fall back to the 4G network, ensuring service continuity. Conversely, when the UE moves to an area with better 5G coverage, coverage-based handover or redirection is configured to migrate the UE back to the 5G network. As a consequence, collaboration analyses with 4G and 5G are mandatory [12–14].

An overview of 4G/5G networks in terms of deployment environments, performance metrics, and implementation scenarios is provided in [15]. The authors of [16] conducted measurements of 4G and non-standalone (NSA) 5G coverage and evaluated the quality of experience (QoE) in Croatian cities in the spring of 2022, although they did not provide an in-depth analysis. The authors of [17] evaluated coverage performance taking both association and coverage events into account; however, the study was primarily focused on analyzing cellular networks using a correlated blockage model. In [18], the influences of the signal propagation environment and noise variance on the coverage situation were considered, with the aim of developing a coverage calculation algorithm to better reflect truth value conditions. However, the authors mainly focused on optimizing the coverage problem in a wireless sensor network (WSN) and on the coverage of a single node with limited application scenarios. The addition of localization accuracy to the coverage calculation algorithm was proposed in [19]. The validity of MR-based coverage estimation in the presence of positional uncertainties was discussed in [19–23]. It is important to note that these studies did not specifically take quantization-related mistakes into account. The quantization error in estimating coverage was discussed in [24], although not using an MR-based approach. Regression clustering was used for the construction of reference signal receiving power (RSRP) maps from a sparse set of measurements in [25]. Lin proposed an MR system in which UEs upload the measurement reports periodically. Based on the acquired measurement reports, the MR system acquires knowledge about the communication environment and uses it to forecast the coverage situation [26]. However, there have been few studies on the reliability reduction of new radio (NR) coverage analysis results caused by incomplete MR.

In related work in [27] involving algorithms used for missing data compensation and true value restoration, quantified quantization and positioning errors in MR-based autonomous coverage estimation were found to stem from inaccurate user positioning. A compensation method for underestimation in path loss modeling was proposed in [28]. The method focuses on calculating reasonable truth values based on instantaneous values. Furthermore, in [29], a method was discussed that compensates for the empirical cumulative distribution function (CDF) of the target power by taking into account the among of missing data in each mesh. However, none of these algorithms involve the optimization of coverage calculation, with limited generalization performance.

The remainder of this paper is organized as follows. Section 2 introduces the motivation and contributions of this paper. Section 3 analyzes the problems associated with traditional algorithms and proposes an optimization algorithm for 5G coverage calculation based on 4G/5G collaboration. Section 4 reports several practical results and an analysis of the optimization algorithm. Section 5 summarizes our conclusions.

2. Motivation and Contribution

Coverage is a key indicator when evaluating the performance of a wireless network. As discussed earlier, some previous studies have investigated coverage calculations and true value compensation. However, many of these proposed algorithms were validated through simulation rather than practical field tests. Additionally, a significant limitation of most current algorithms is that they are designed for single-frequency and single-system scenarios. Furthermore, a majority of these algorithms are not applicable to 5G networks and lack analysis from a multifrequency collaboration perspective, which can result in biased coverage. Moreover, since 5G networks adopt new technologies and new frequency bands, accurate network planning heavily relies on coverage calculations. If 5G network coverage cannot be accurately evaluated, it may adversely impact the overall deployment and performance of the network. Therefore, it is imperative to develop cutting-edge algorithms and thorough assessments to guarantee precise and trustworthy coverage evaluation in the context of 5G networks.

Based on the above observations, we were inspired to propose a novel extrapolation algorithm that leverages compensated 4G evaluation to optimize 5G coverage. To address the bias of the coverage findings, the goal of this study is to optimize the coverage calculation method in the wireless communication domain. For 5G coverage detection, a new coverage calculation algorithm is designed by utilizing the 4G–5G cooperative analysis method with the 4G network as a reference. The proposed algorithm considers the residency time, RSRP, and other aspects of 4G and 5G networks. Furthermore, it integrates multi frequencies, systems, and operators to achieve a more realistic restoration of the actual 5G coverage. The proposed algorithm enhances the dependability, fosters 4G/5G network collaboration, and enhances 5G network quality, and thus aligns with the goal of developing a technologically advanced, high-quality, and well-covered 5G network. Additionally, it offers valuable insights for enhancing the coverage of future mobile communication systems.

This study is based on the world's first commercially available SA network that offers the largest coverage. To our knowledge, the most common equipment vendors were used in this study to build the environment and conduct technical field tests. It is presented on the coverage of specific areas where MRs have been field conducted. To the best of our knowledge, this is the first study that collaborates 4G/5G multi-frequency and inter-system coverage calculations, with analyzing and validating steps from both theoretical and experimental perspectives. The advantages of the optimization algorithm in comparison to the traditional coverage algorithm are also highlighted, which helps to provide an important reference for future 5G base station (gNodeB/gNB) blinding. Moreover, this study can serve as a benchmark for other mobile network operators (MNO) or countries, especially considering the projected continuous growth in 5G traffic in the coming years. Furthermore, the proposed method's generality and universality provide the potential for it to be applied to 6G network coverage detection in the future.

Our results show that, compared with conventional methods, the proposed method achieves an accuracy improvement of approximately 15.4 times on the average target coverage estimation task.

3. Detailed Description

Coverage calculation is used to assess the state of wireless networks. In this section, we introduce the problem analysis of the traditional coverage calculation algorithm and the proposed 5G coverage calculation optimization algorithm based on 4G/5G collaboration.

3.1. Problem Analysis of Traditional Coverage Calculation Algorithm

The weak coverage ratio (WCR) is mainly used as a coverage evaluation scheme in traditional coverage calculation algorithms. WCR is calculated using the RSRP in the MR periodically reported by the users residing in the 5G network. Whether a user can be resident in 5G or not is strongly influenced by the interoperability parameter (A2/B1). As shown in Figure 1, when the RSRP of the 5G user decreases to the interoperability threshold, the network falls back to the 4G, preventing further reporting of 5G MRs. The high inter-system interoperability threshold can lead to incomplete 5G MR statistics, especially for weak coverage areas. Consequently, identifying coverage issues in such areas becomes challenging. These incomplete data fail to reflect the actual 5G coverage performance, which hinders accurate evaluations.

To validate the assertions mentioned above, we conducted an experiment in 5G SA commercial networks. In this experiment, we assessed the impact of two different inter-operability threshold configurations on the coverage ratio evaluation task by sampling the same area simultaneously. The interoperability configuration parameters are shown in Table 1. The test results are shown in Figures 2 and 3.

Table 1. Interoperability Configuration Parameters.

	A2	B1
Configuration 1	−115 dBm	−111 dBm
Configuration 2	−121 dBm	−115 dBm

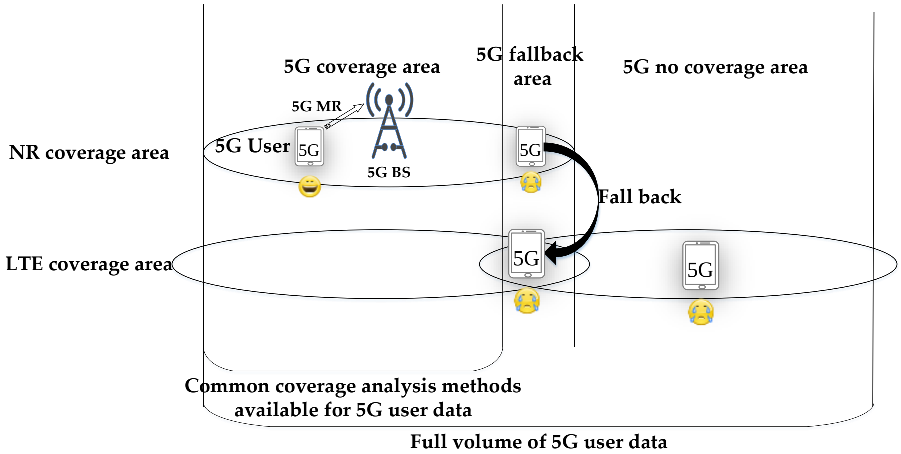


Figure 1. 4G/5G Coverage.

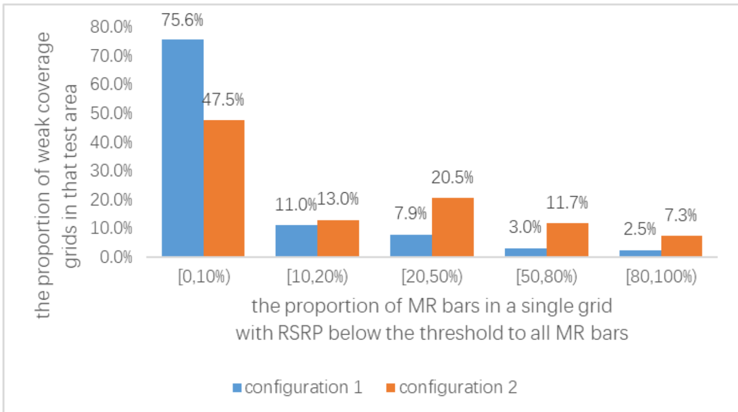


Figure 2. Comparison of the impact of different interoperability thresholds on the WCR.

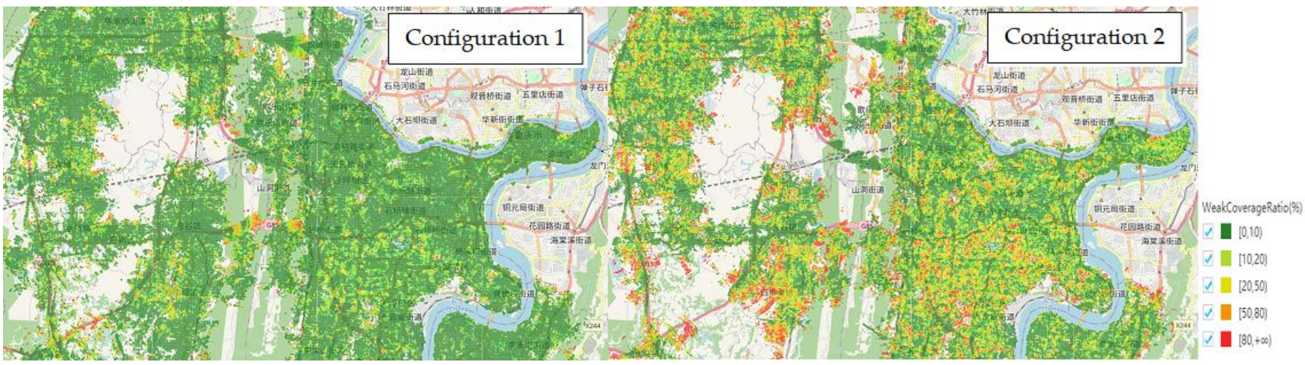


Figure 3. Coverage ratio in different configurations.

We employed the common grid-level WCR judgment threshold, where the criterion is that the percentage of RSRPs less than −105 dBm exceeds 20%. Figures 2 and 3 show the mapping of WCR at the grid level within the test area and the comparison of the impact of different interoperability thresholds on the WCR, respectively. In Figure 2, the horizontal axis represents the proportion of MR bars in a single grid with RSRP below the threshold of all MR bars, while the vertical axis represents the proportion of grids with weak coverage in the test area. As can be seen in Figure 2, the WCR of Configuration 1 in this area is 13.4%, whereas the WCR of Configuration 2 reaches 39.5%, nearly three times higher. This is because the interoperability threshold of Configuration 1 is higher than that of Configuration 2, which results in the 5G users in Configuration 1 being more likely to fall back to 4G and the related parts of the UEs being unable to report the 5G MR. The lower the number of weak-coverage RSRPs that can be detected, the better the 5G coverage evaluation results are. However, in reality, many 5G users are forced to be resident in 4G, making it challenging to detect these coverage problems from the 5G side. This aligns with what the theoretical analysis revealed.

We propose an optimized approach to relieve the above-mentioned issues, which we will introduce in Section 3.2.

3.2. A 5G Coverage Calculation Optimization Algorithm Based on 4G/5G Collaboration

This study introduces an optimization algorithm based on 4G/5G collaboration for determining the true value of 5G coverage conditions, mitigating the bias issues in the conventional coverage algorithms. The proposed algorithm combines the 5G–5G inner-system MR and the 4G–5G inter-system MR, and weights them according to the time duration–residency ratio. The output of the algorithm is the comprehensive 5G coverage evaluation results. The overall workflow is illustrated in Figure 4.

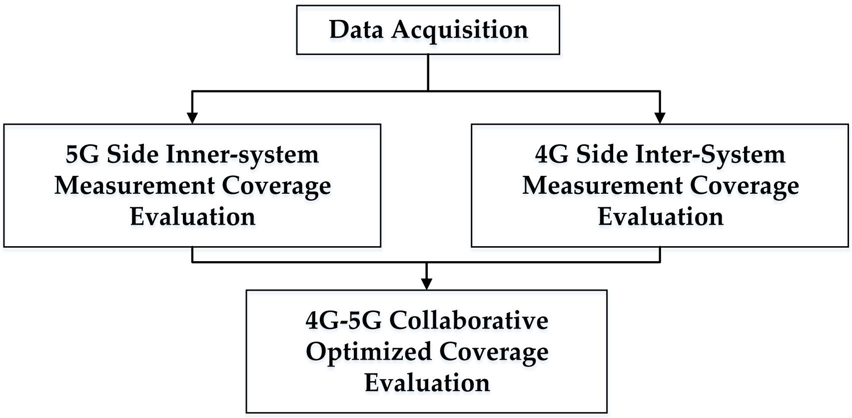


Figure 4. 5G Coverage Optimization Algorithm Flow based on 4G/5G Collaboration.

Firstly, 4G MRs, 5G MRs, and essential operational parameters are collected according to the data acquisition module. Then, the RSRP reported by the 5G inner-system MR is calculated and grid-geographized through the 5G-side inner-system measurement coverage evaluation module. Next, the 5G RSRP reported by the 4G inter-system MR is calculated and grid-geographized through the 4G-side inter-system measurement coverage evaluation module. Finally, through the 4G–5G collaboration optimization coverage evaluation module, the 5G inner-system results and the 4G inter-system results are merged to produce the optimized 5G coverage results, which serve as the final output. We will introduce each module individually in the following subsections.

3.2.1. Data Acquisition Module

Firstly, both periodic 5G inner-system measurement and 4G-side 5G inter-system measurement functions are enabled with the same periodic configuration. During this period, users residing on 5G in the Radio Resource Control (RRC) connected state periodically report 5G MRs to gNodeB. Simultaneously, 5G users residing on 4G in the RRC connected state periodically trigger inter-system measurement of the 5G frequency point, thus reporting 4G MRs to the 4G base station (eNodeB). An illustration of this process is shown in Figure 5. The data to be acquired, along with their descriptions, are shown in Table 2.

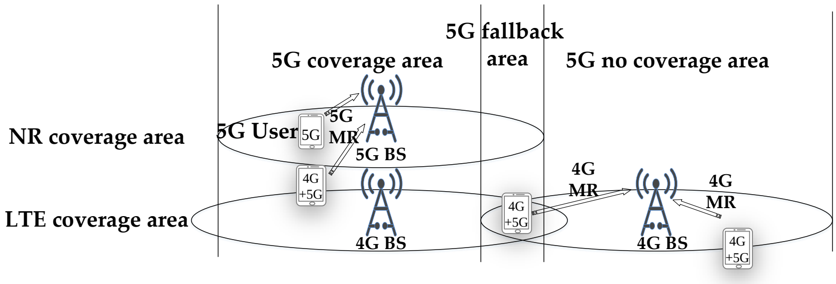


Figure 5. Periodic reporting MR of 5G users resident on 4G/5G networks.

Table 2. Data Acquisition for Optimization Algorithms.

Data Type	Acquisition Time	Description
5G Parameters	/	Obtain latitude and longitude information of gNodeB for locating 5G users resident in the 5G
5G MR	At least 1 day	Obtain localization and RSRP of 5G side
5G Call Statistics	Same as 5G MR	Obtain call statistics of 5G user residents in 5G for weighting
4G Parameters	/	Obtain latitude and longitude information of eNodeB for locating 5G users resident in 4G.
4G MR	Same as 5G MR	Obtain localization and RSRP of 4G side
4G Call Statistics	Same as 5G Call Statistics	Obtain call statistics of 5G user residents in 4G for weighting

Periodic inter-system measurement applies to all network modes of Long-Term Evolution (LTE), NSA Single Mode, NSA/SA Dual Mode, and SA Single Mode. The following points should be noted when enabling periodic 4G–5G inter-system measurement:

(1) The eNodeB should place the MR for inter-frequency/inter-system MR for NSA-capable UEs since SA UEs also support NSA capability;
(2) To ensure an adequate number of frequency points, the LTE cell should configure the NR neighbor frequency and the maximum number of inter-frequency and inter-system measurement frequency points;
(3) The consistency between the period of 4G/5G MR and 4G/5G call statistics should be ensured. Typically, the default sampling period is set to 10 s. Due to the need of the minimized changes to the actual network, the sampling period remains unchanged, with 10 random UEs reporting MR each time. The process of data acquisition requires at least one sampling session per day to guarantee the safety and reliability of data analysis.
(4) The UE capability detection function should be enabled for two main purposes. Firstly, it is used to differentiate between LTE-only and LTE-NR dual-system users, as LTE-only users cannot use the NR network. Consequently, data from LTE-only users have no significance for 5G coverage evaluation. Therefore, only 4G–5G dual-system users are randomly selected for periodic inter-system measurements and reported to ensure a more accurate analysis. Secondly, it distinguishes the 4G–5G dual-system users who use the Voice of LTE (VoLTE). Because the VoLTE usage strategy is a user-side controllable behavior. The actual network coverage status cannot be reflected in the RSRPs of UEs that fall back to 4G. Therefore, it is necessary to exclude users who are using VoLTE based on 4G–5G dual-system users to ensure data reliability.
(5) MR includes performance indicators related to network coverage such as RSRP, location information, UE capability, etc. These reports are labeled as geographical location information related to UE and neighboring base stations. Thus, MRs should firstly be sent to the service base stations for localization, and then coverage maps are drawn. The positioning, obtained through MR, is then mapped with available map resources to distinguish between indoor and outdoor statuses.

(6) Grid positioning determines the specific position (longitude and latitude) of UEs in the wireless network. Currently, common positioning methods achieve an accuracy of about 50 meters. As these methods mainly use triangle positioning with beam information as assistance [30], grid sizes should be set to a range greater than this positioning accuracy. The proposed algorithm primarily aims to restore hidden weak coverage areas, and the coverage range of a gNodeB is much greater than 50 m. The positioning accuracy is therefore tolerable. Additionally, if an MR is located in the grids' critical area, it could belong to any neighbor grid while not repeating the statistics.

Table 3 shows the primary objects and descriptions in 5G MR and 4G MR.

Table 3. 5G/4G MR Key Object.

Acquisition Object	Event	Description
NR MR	PERIOD_INTRA_FREQ_MEASUREMENT	Localization, 5G Inner-Frequency RSRP
	PERIOD_PRIVATE_UE_MEASUREMENT	Assistant Localization
	PERIOD_PRIVATE_UL_BEAM_INFO	Assistant Localization
LTE MR	PERIOD_INTRA_FREQ_MEASUREMENT	Localization, 4G RSRP
	PERIOD_PRIVATE_UE_MEASUREMENT	Assistant Localization
	UE_CAPABILITY_INFORMATION	Identify VoLTE Users
	UE_CAPABILITY_INFORMATION_HOIN	Identify 4G/5G Dual-System Users
	PERIOD_INTER_RAT_MEASUREMENT	4G–5G Inter-System Measurement RSRP

3.2.2. Measurement Evaluation Module

Firstly, we introduce the 4G Side Inter-System Measurement Evaluation. Figure 6 illustrates how the module organizes and evaluates the data gathered from the 4G side.

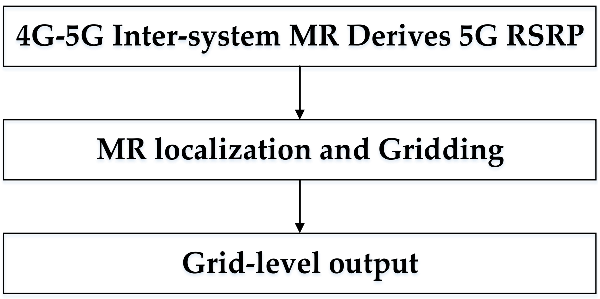


Figure 6. 4G Side Inter-System Measurement Evaluation Process.

As shown in Figure 6, samples that meet the criteria from the 4G–5G periodic inter-system MRs are first filtered out the data corpus. It is noted that 5G neighbor RSRPs that are measured multiple times can be reported in a single MR. In such cases, the neighbor RSRP with the highest 5G is taken as the reported 5G RSRP of this MR. MRs with 5G RSRPs lower than the WCR threshold are marked as a weak-coverage MR. Next, the localization algorithm is used to determine the MR location. Then, the gridding 5G RSRP is employed for each 4G–5G periodic inter-system MR to a specific grid. Finally, the grid data are aggregated to calculate the inter-system WCR at the grid level, which is determined by two factors: first, the number of inter-system MRs at the grid level (the number of inter-system MRs in the grid); second, the number of inter-system weak-coverage MRs (the number of inter-system weak-coverage MRs in the grid), Specifically, we show the above-mentioned calculation as follows:

$$\begin{aligned} Cn, \mathrm{inter} - system &= \begin{pmatrix} c_{1,4G} & c_{2,4G} & \cdots & c_{n,4G} \end{pmatrix} \times 100\% \\ &= \begin{pmatrix} N_{1,weak-covering}/N_{1,full-covering} & N_{2,weak-covering}/N_{2,full-covering} & \cdots & N_{n,weak-covering}/N_{n,full-covering} \end{pmatrix} \times 100\% \end{aligned} \tag{1}$$

where Cn, inter − system represents the 4G side inter-system 5G WCR matrix; n represents the number of grids in the area; $c_{n,4G}$ indicates the 4G side inter-system 5G WCR of the nth grid; $N_{n,weak-covering}$ represents the number of 4G-side inter-system MR entries with RSRPs below the threshold in the nth grid; and $N_{n,full-covering}$ denotes the total number of 4G side inter-system 5G MR entries of the nth grid.

We will skip the detailed discussion on the 5G side inner-system measurement and evaluation module as it is similar to the 4G inter-system measurement and evaluation module. It should be noted that one should maintain the consistency of factors for WCR threshold, statistical time, period and frequency point information, and grid division with the 4G inter-system measurement and evaluation module.

We present the 5G side inner-system 5G WCR matrix as follows:

$$\begin{aligned} &\mathrm{Cn}, inner{-}\mathrm{system} = \begin{pmatrix} c_{1,5G} & c_{2,5G} & \ldots & c_{n,5G} \end{pmatrix} \times 100\% \\ &= \begin{pmatrix} M_{1,\mathrm{weak-covering}}/M_{1,\mathrm{full-covering}} & M_{2,\mathrm{weak-covering}}/M_{2,\mathrm{full-covering}} & \ldots & M_{\mathrm{n,weak-covering}}/M_{\mathrm{n,full-covering}} \end{pmatrix} \times 100\% \end{aligned} \tag{2}$$

where Cn, *inner*−system indicates the 5G side inner-system 5G WCR matrix; n represents the number of grids in the area; $c_{n,5G}$ donates the 5G side inner-system 5G WCR of the nth grid; $M_{n,weak-covering}$ represents the number of 5G-side inner-system MR entries with RSRP below the threshold in the nth grid; and $M_{n,full-covering}$ donates the total number of 5G side inner-system 5G MR entries of the nth grid.

3.2.3. 4G–5G Collaboration Optimization Evaluation and Combination Module

This module combines the grid-level 5G inner-frequency coverage evaluation and the 4G-side inter-system coverage evaluation to obtain the 5G WCR truth reduction results. The two types of MR are influenced by user behavior, and the direct addition cannot restore the actual situation of the 5G network. Therefore, an algorithm using the weighting of duration-residency ratios is proposed, which is shown in Figure 7.

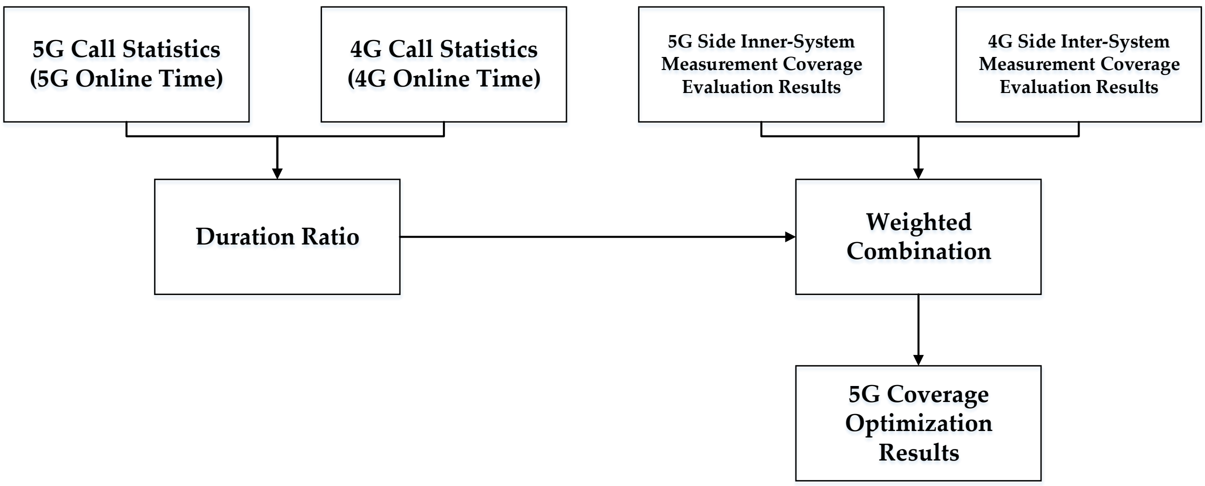


Figure 7. 5G Coverage Truth Reduction Process Based on 4G/5G Collaboration.

As shown in Figure 7, the 4G/5G call statistics can be used to obtain the grid-level 4G/5G time duration of the user in the RRC-connected state. The 4G/5G time duration-residency ratio matrix is obtained according to

$$K = \begin{pmatrix} k_{1,4G} & k_{1,5G} \\ k_{2,4G} & k_{2,5G} \\ \vdots & \vdots \\ k_{\mathrm{n},4G} & k_{\mathrm{n},5G} \end{pmatrix} = \begin{pmatrix} R_{1,4G}/R_{1,total} & R_{1,5G}/R_{1,total} \\ R_{2,4G}/R_{2,total} & R_{2,5G}/R_{2,total} \\ \vdots & \vdots \\ R_{\mathrm{n},4G}/R_{\mathrm{n},total} & R_{\mathrm{n},5G}/R_{\mathrm{n},total} \end{pmatrix} \tag{3}$$

$$R_{\mathrm{i},total} = R_{\mathrm{i},4G} + R_{\mathrm{i},5G} \tag{4}$$

where n donates the total number of grids in a certain area, $k_{\mathrm{n},4G}$ and $k_{\mathrm{n},5G}$ represent the duration-residency ratio under 4G and 5G in the nth grid, respectively. $R_{\mathrm{n},4G}$ and $R_{\mathrm{n},5G}$ donate the duration of the user in the RRC-connected state under 4G and 5G in the nth grid, respectively. $R_{\mathrm{n},total}$ indicates the addition of the duration-residency ratio of the user in the RRC-connected state under 4G and 5G in the nth grid.

Based on the output results of the 4G-side inter-system measurement and evaluation module and the 5G-side inner-system measurement and evaluation module, the grid-level WCR matrix was created, as follows:

$$\begin{aligned} \mathrm{C} &= \begin{pmatrix} \mathrm{Cn,\,inter-system} \\ \mathrm{Cn,}\,inner\mathrm{-system} \end{pmatrix} = \begin{pmatrix} c_{1,4G} & c_{2,4G} & \cdots & c_{n,4G} \\ c_{1,5G} & c_{2,5G} & \cdots & c_{n,5G} \end{pmatrix} \\ &= \begin{pmatrix} \mathrm{N_{1,weak-covering}}/\mathrm{N_{1,full-covering}} & \mathrm{N_{2,weak-covering}}/\mathrm{N_{2,full-covering}} & \cdots & \mathrm{N_{n,weak-covering}}/\mathrm{N_{n,full-covering}} \\ M_{\mathrm{1,weak-covering}}/M_{\mathrm{1,full-covering}} & M_{\mathrm{2,weak-covering}}/M_{\mathrm{2,full-covering}} & \cdots & M_{\mathrm{n,weak-covering}}/M_{\mathrm{n,full-covering}} \end{pmatrix} \times 100\% \end{aligned} \quad (5)$$

Finally, the optimized WCR calculation results for the full amount of grids in the area can be obtained based on the 4G/5G duration–residency ratio matrix and the grid-level weak coverage result matrix, as

$$\begin{aligned} \mathrm{F} = K'.*C &= \begin{pmatrix} k_{1,4G} & k_{1,5G} \\ k_{2,4G} & k_{2,5G} \\ \vdots & \vdots \\ k_{\mathrm{n},4G} & k_{\mathrm{n},5G} \end{pmatrix}'.* \begin{pmatrix} c_{1,4G} & c_{2,4G} & \cdots & c_{n,4G} \\ c_{1,5G} & c_{2,5G} & \cdots & c_{n,5G} \end{pmatrix} \\ &= \begin{pmatrix} k_{1,4G}\cdot c_{1,4G} + k_{1,5G}\cdot c_{1,5G} & k_{2,4G}\cdot c_{2,4G} + k_{2,5G}\cdot c_{2,5G} & \cdots & k_{n,4G}\cdot c_{n,4G} + k_{n,5G}\cdot c_{n,5G} \end{pmatrix} \end{aligned} \quad (6)$$

where F is an n-element vector, which is the result of 5G coverage truth reduction of n grids in the area, and is the synthesis operation of matrix multiplication taking the main diagonal result. The algorithm can be simply understood as a weighted combination based on the 4G/5G duration–residency ratio for the 5G WCR of 4G inter-system and 5G inner-system at the grid level to obtain the 5G coverage truth reduction result.

3.2.4. Algorithmic Functionality Expansion

The optimization algorithms can be extended, e.g., single-band coverage evaluation, and inter-operator evaluation. Brief descriptions are given separately.

(1) Single-Band Coverage Evaluation

Fifth–generation single-band coverage can be restored based on 5G inner-frequency, 5G inter-frequency, and the 4G network. Take the NR 3.5 GHz and 2.1 GHz bands as an example: 3.5 GHz users prioritize residents in NR 3.5 GHz with better coverage, and fall back to the LTE 2.1 GHz network when the coverage is weak, as shown in Figure 8. At this time, if the coverage of 2.1 GHz NR needs to be analyzed singularly, 3.5 GHz NR users and fallback to LTE 2.1 GHz should also be calculated in the combined evaluation. The traditional coverage evaluation cannot be realized. In this case, the optimization algorithm can be used to calculate the NR 2.1 GHz WCR based on the 2.1 GHz MR reported by 5G inner-frequency measurements, the 3.5 GHz MR reported by 5G inter-frequency measurements, and the 2.1 GHz MR reported by 4G inter-system measurements. Combined with their respective time duration–residence ratios, the matrix can be expanded to calculate the NR 2.1 GHz WCR.

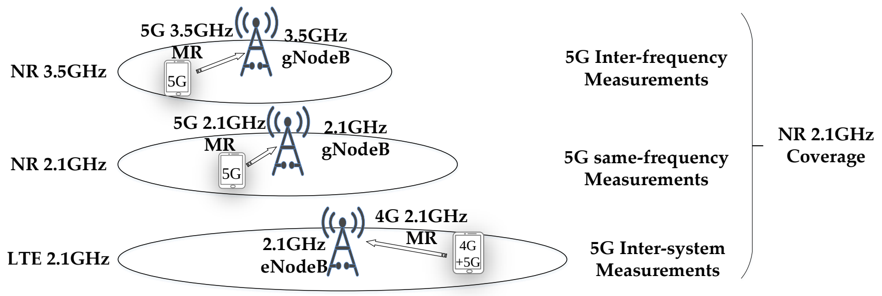


Figure 8. Example of single-band evaluation.

(2) Inter-Operator Evaluation

For inter-operator evaluation, the present optimization algorithm can be partially applied. In the data acquisition module, when the periodic inter-frequency measurement of the 5G-side users of the home operator is performed, the 5G frequency point of the inter-operator is also configured. RSRPs of the inter-operator are measured and MRs reported as shown in Figure 9. It should be noted that one MR only contains one frequency band to report, and the inter-frequency event contains details about the primary service cell of the home operator and the neighbor cell of the inter-operator.

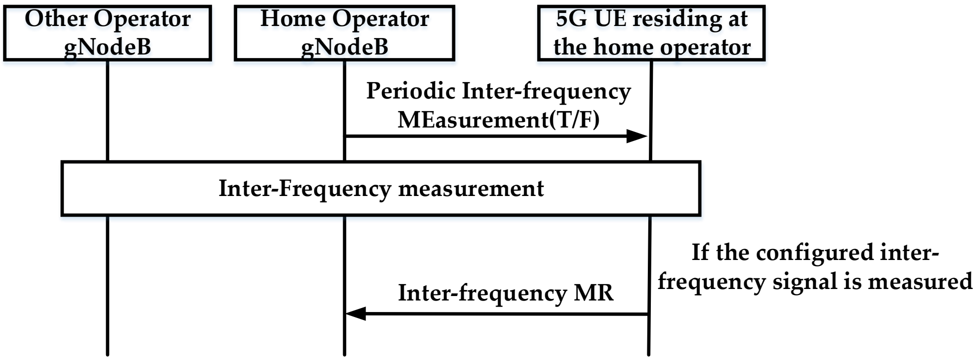


Figure 9. 5G-Side Inter-Operator Measurement Flow.

Grid-level competitive comparison results are obtained by performing coverage calculations on the acquired inner-frequency 5G coverage of the home operator and the inter-frequency 5G coverage of the inter-operator. Comparisons might reveal areas of competitive advantage or disadvantage. They can efficiently and accurately compare multi-operator network coverage capabilities, and realize network analysis and planning based on competitive comparisons. Since the whole measurement process is completed in the subscribers of the carrier and network, there is no impact on inter-operators.

4. Performance Analysis

4.1. Test Environment

The data are processed from field measurements with a large sample size. The test analysis introduced focuses on comparison tests for 5G coverage truth restoration optimization algorithms based on 4G/5G collaboration.

This performance test was conducted in a commercial LTE/NR network. The interoperability parameter thresholds for mobility for testing are configured as A2 = −121 dBm and B1 = −115 dBm. The area is a typical test scenario that covers several urban areas, towns, residential buildings, and small commercial streets. The test area is a multi-cell networking scenario with small station spacing. The environment is shown in Figure 10. Of the test area, 23 square kilometers are covered by 167 SA gNodeBs and 89 eNodeBs.

Figure 10. Test Area.

Table 4 displays the carrier configuration in the test area.

Table 4. Carrier Configuration.

System	Carrier (GHz)	Band (MHz)	Band	Central Frequency Point (MHz)
4G	2.1 (few)	40	B1	2130
5G	3.5	200	N78	3500
	2.1 (lot)	40	B1	2130

Table 5 displays the pathloss models in the test area according to TR 36.873 [31].

Table 5. Pathloss models.

Scenario	Model	LOS/NLOS
Indoor	3D-UMA	NLOS
Outdoor	HATA	LOS

4.2. Traditional Algorithm vs. Optimization Algorithm Comparison Analysis

Based on Section 3.2, data acquisition was carried out in the same area for the traditional inner-frequency coverage algorithm and the optimization algorithm with multi-system collaboration, respectively.

The RSRP in each MR acquired from the periodic inter-system measurements and the inner-system measurements are compared in the same grid, as shown in Figure 11.

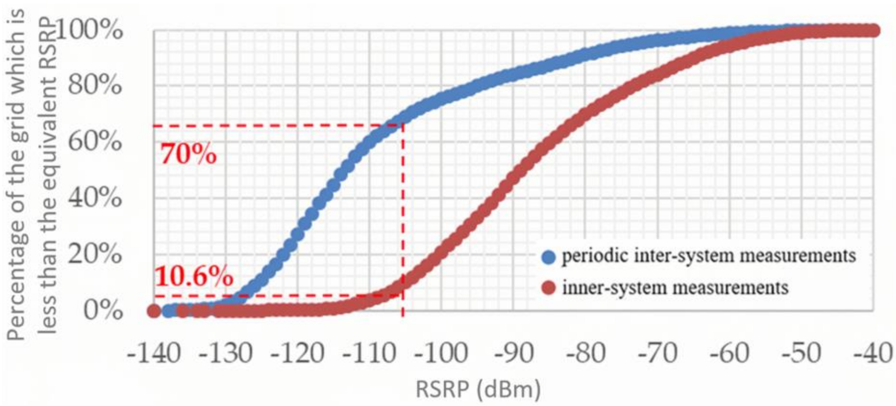


Figure 11. Comparison of MR-level RSRP distributions.

The blue curve shows the RSRP distribution of periodic inter-system measurements on the 4G side. The red curve shows the RSRP distribution of inner-system measurements on the 5G side. The X axis shows the RSRP in dBm. The Y axis shows the percentage of the grid that is less than the equivalent RSRP. It can be seen that the RSRPs acquired by both methods are concentrated between −140 and −40 dBm. The maximum difference point is −105 dBm, i.e., 70% of RSRPs less than −105 dBm were measured by inter-system measurement on the 4G side, while only 10.6% of RSRPs less than −105 dBm were measured by the inner-system on the 5G side, which is a 59.4% difference of nearly seven times. It can be seen that using less than −105 dBm as the weak coverage judgment threshold can maximize the distinction between the two types of measurements.

We acquired a total of 90,700,000 5G inner-system MRs and 3,260,000 4G inter-system MRs in this test area, and divided it into 7507 50 m by 50 m grids for mapping all the MRs, and achieved the results of the area test as depicted in Figure 12.

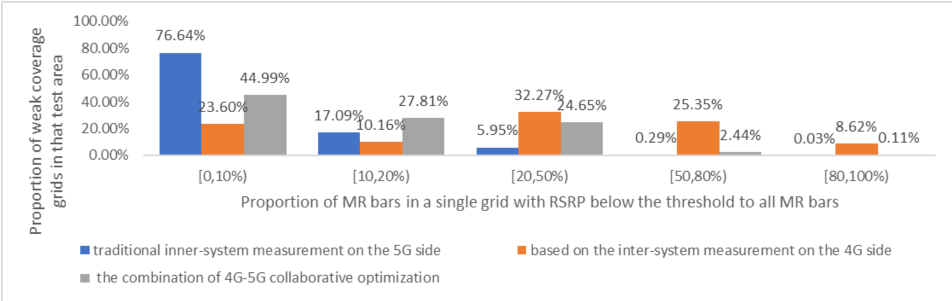
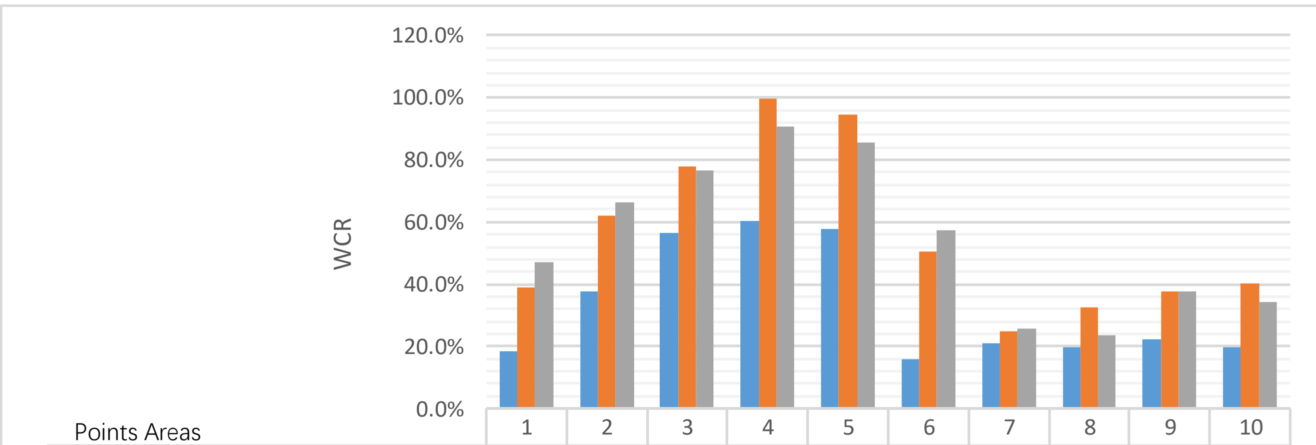


Figure 12. Coverage evaluation results (Traditional algorithms vs. Optimization algorithms).

The X axis in Figure 12 represent the proportion of MR bars in a single grid with RSRP below the threshold to all MR bars; the Y axis shows the proportion of weak-coverage grids in that test area. Any grid that does not meet −105 dBm@80% is uniformly defined as a weak-coverage grid, i.e., the threshold for weak coverage judgment at the grid level is that the percentage of RSRPs lower than −105 dBm is more than 20%. It can be seen that 6.27% of the weak coverage area can be found based on the traditional 5G side inner-system measurement coverage evaluation. In total, 66.24% of the weak coverage area can be found based on the inter-system measurement coverage evaluation on the 4G side, while 27.20% of the weak coverage area can be found based on multi-system collaborative optimization, which is nearly 21% more than the weak coverage grids obtained from the 5G inner-system algorithm, about 4.3 times. It can be seen that the algorithm proposed in this study can find more weak coverage grids compared to the traditional coverage evaluation algorithm, which is consistent with the results of the theoretical analysis in Section 3.

4.3. Validation of Coverage Evaluation Algorithms vs. Field Drive Test

We evaluated the coverage of the same area based on the traditional and optimized coverage evaluation algorithms and the actual field drive test (DT) to estimate which algorithm can more realistically restore the actual coverage situation. Due to the strict conditions and resource cost issues that need to be considered in the DT, we sampled 10 random points to compare the differences between the traditional/new algorithms and the true values. Ten random points, including squares and streets, were selected in the test area from Section 4.1. Any grid that does not satisfy −105 dBm@80% was uniformly defined as a weak-coverage grid. Figure 13 compares the outcomes from the 10 points.



Points Areas	1	2	3	4	5	6	7	8	9	10
Traditional Algorithm WCR	18.3%	37.6%	56.5%	60.2%	57.8%	15.7%	20.9%	19.9%	22.2%	19.7%
Multi-Frequency Collaboration Algorithm WCR	39.0%	61.9%	77.7%	99.8%	94.7%	50.7%	25.0%	32.5%	37.6%	40.3%
DT WCR	47.1%	66.3%	76.8%	90.6%	85.4%	57.5%	25.6%	23.4%	37.9%	34.3%

Figure 13. Test area coverage evaluation results (Algorithms vs. DT).

As can be seen in Figure 13, the traditional 5G inner-system algorithm differs a lot from the actual coverage, with errors between 3.5% and 41.8%, with an average error of 21.6% and a variance of 1.3%. Only a small number of coverage voids can be restored, and there is a gap with the true value of the actual coverage, and the error fluctuation is large. The findings of the multi-system collaboration-based 5G coverage optimization algorithm are closer to the actual coverage, with errors ranging from 0.3% to 9.3%, with an average error of 1.4% and a variance of 0.4%. When compared to the conventional technique, the error is reduced by 15.4 times, and the variance is reduced by 3.3 times. It can detect more problematic grids and restore the actual coverage of the area, and the error fluctuation is reduced.

It can be concluded that the multi-system collaboration 5G coverage truth restoration optimization algorithm results can be approximated to the field road test results, i.e., it can realistically restore the 5G coverage.

4.4. Indoor Scenario vs. Outdoor Scenario Comparison Analysis

We used the method in Section 3.2 to acquire data for indoor and outdoor scenarios in the test area of Section 4.1 and conducted the actual walking test (WT) for the indoor scenario. Grids that did not satisfy the −105 dBm@80% were uniformly defined as weak-coverage grids. The results are shown in Figure 14.

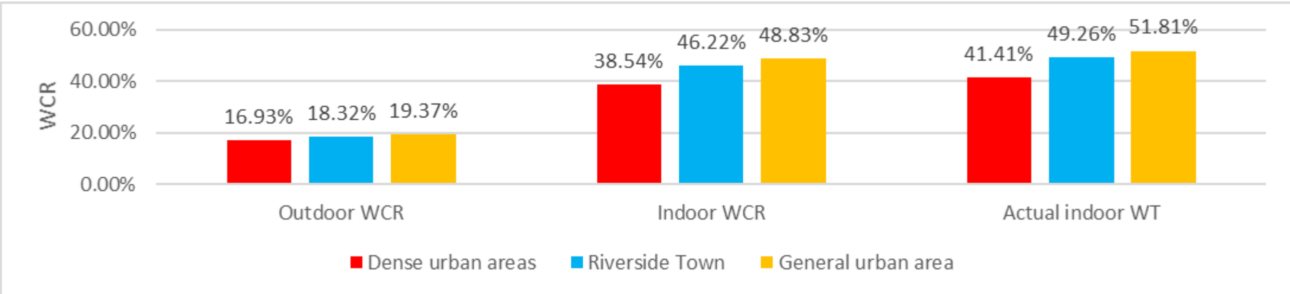


Figure 14. Test area coverage evaluation results (Indoor vs. Outdoor).

In Figure 14, the three data sets on the left are the outdoor weak coverage restoration results, the center is the indoor weak coverage restoration results, and the right is the actual indoor WT results. The X axis shows the categorization of the scenarios: red is the dense urban area, blue is the riverside town, and orange is the general urban area; the Y axis is the WCR of different scenarios. The outdoor 5G WCR of the dense urban area is only 16.93%; however, the indoor 5G WCR reaches 38.54%, which is 21.61% higher than the outdoor WCR, and the difference of the actual indoor WT value is 2.87%. The outdoor 5G WCR of the riverside towns is only 18.32%, and the indoor 5G WCR reaches 46.22%, which is 27.90% higher than the outdoor WCR, and the difference of the actual indoor WT value is 3.04%. The outdoor 5G WCR of the general urban areas is only 19.37%, and the indoor 5G WCR reaches 48.83%, which is 29.46% higher than the outdoor WCR, and the difference of the actual indoor WT value is 2.98%.

It can be seen that, no matter which scenario, the difference in indoor and outdoor 5G WCR obtained by the 5G coverage optimization algorithm based on multi-system collaboration is about 26.32%. However, the difference between the indoor restoration results and the results measured in the actual network is about 2.96%, which is the same. Therefore, we can see that there are significant differences between indoor and outdoor WCR. Indoor 5G coverage is worse than outdoor. However, both indoor and outdoor weak coverage areas can be reduced respectively through the optimization algorithm based on multi-system collaboration, further determining whether the area can be constructed with a 5G indoor distribution system.

4.5. Impact of Periodic 4G/5G Inter-System Measurements to the Network

In this section, we conducted a practical test to evaluate the influence of activating periodic 4G/5G inter-system measurements on the network. We turned on the periodic 4G/5G inter-system measurements from March 22nd to March 23rd and continuously observed the data of 10 UEs during the week. The assessment encompassed statistical evaluations of the 5G drop ratio, RRC establishment success ratio, handover success ratio, and user experience rate.

Firstly, the change in the 5G drop ratio was analyzed, as shown in Figure 15.

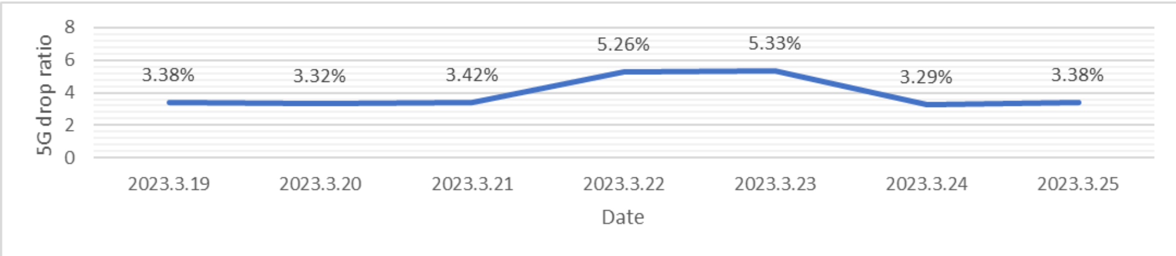


Figure 15. 5G drop ratio test result.

Figure 15 presents the date on the X axis and the corresponding 5G drop ratio in the Y axis. Between March 19th and March 21st, the 5G drop ratio of the UE remained stable between 3.38% and 3.42% when periodic 4G/5G inter-system measurements were not enabled. When the periodic 4G/5G inter-system measurement was enabled, the 5G drop ratio of the UE improved to approximately 5.3%, signifying a 1.93% increase. After the periodic 4G/5G inter-system measurement was disabled, the 5G drop ratio reverted to the initial level. This is because, during the measurement period, according to the protocol, the UE cannot send and receive data. If users engage in voice services at this time, it causes call drop to occur, consequently elevating the call drop ratio.

Secondly, the change in the RRC establishment success ratio of UE was analyzed. The results are shown in Figure 16.

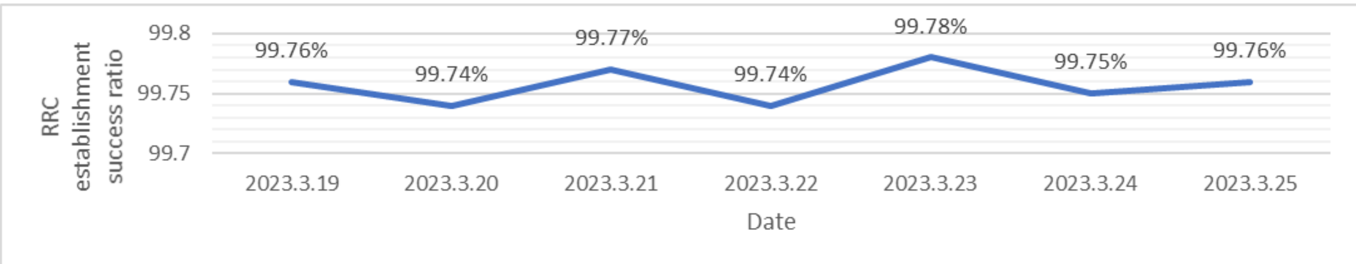


Figure 16. RRC establishment success ratio test result.

In Figure 16, regardless of whether the periodic 4G/5G inter-system measurement was enabled or not, the RRC establishment success ratio of the UE was still relatively stable and stayed at around 99.76%. This is because, before the UE enables the periodic 4G/5G inter-system measurement, it is already in the RRC-connected state. It does not affect the RRC establishment success ratio of the UE.

Thirdly, as illustrated in Figure 17, the variation in the handover success ratio of the UE is analyzed.

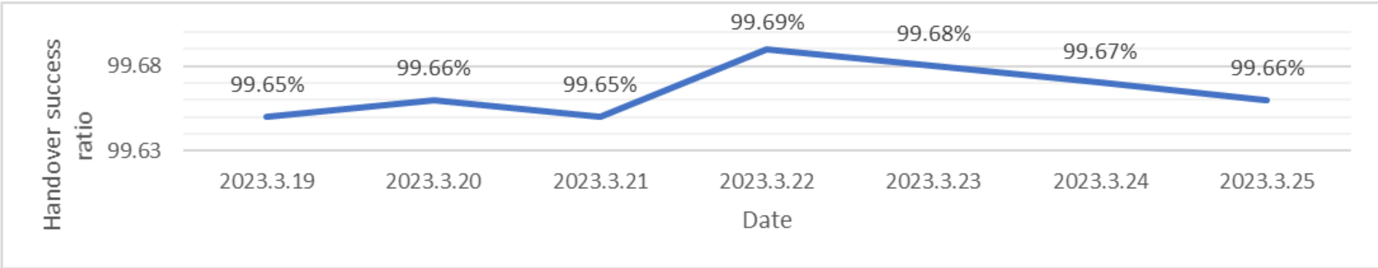


Figure 17. Handover success ratio test result.

In Figure 17, on 19–21 March, when the periodic 4G/5G inter-system measurement was not enabled, the handover success ratio of the UE was between 99.65% and 99.66%. When the periodic 4G/5G inter-system measurement was enabled, the handover success ratio of the UE increased to approximately 99.69%. When the inter-system measurement was disabled, the SA handover success ratio returned to its previous level. Enabling measurement between the 4G/5G inter-system did not cause a decrease in the handover success ratio. Therefore, there was no negative impact on the network. It can be shown that enabling the periodic 4G/5G inter-system measurements causes the UE to periodically measure the neighboring 5G cells, increasing the likelihood of handovers and ultimately enhancing the handover success ratio.

Finally, the impact of the UE user experience rate was analyzed. The results are shown in Figure 18.

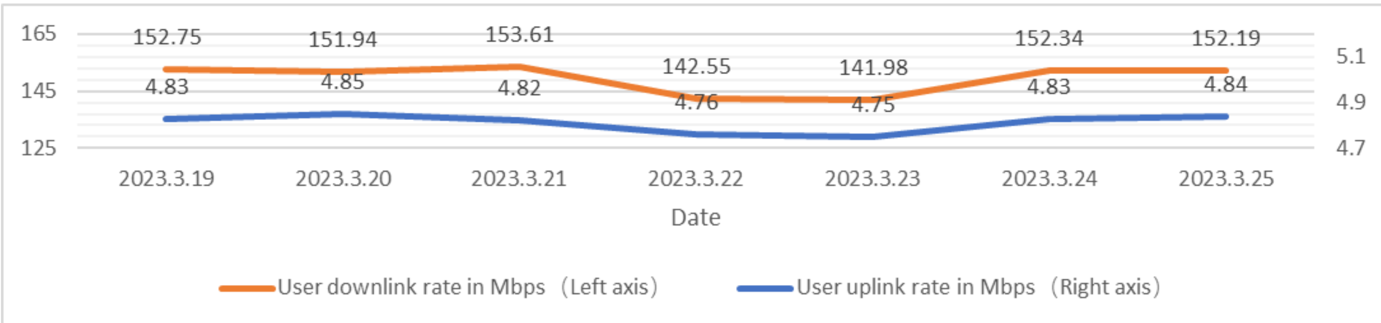


Figure 18. UE user experience rate test result.

In Figure 18, the date and user rate (in Mbps) are indicated by the X and Y axes, respectively. The blue curve shows the uplink rate, while the red curve shows the downlink rate. On 19–21 March, when the periodic 4G/5G inter-system measurements were disabled, the average downlink rate remained stable, ranging between 151.94 and 153.61 Mbps, while the average uplink rate ranged between 4.82 and 4.85 Mbps. When the periodic 4G/5G inter-system measurement was enabled, the downlink average rate decreased to about 142 Mbps, constituting a 6.6% reduction. The uplink average rate decreased to about 4.75 Mbps, with a decrease of 1.8%. After the periodic 4G/5G inter-system measurements were disabled, both the downlink and the uplink average rates returned to their original level. Analysis of the rate decrease problem indicates that enabling the periodic 4G/5G inter-system measurement, according to the protocol, results in the UE being unable to send and receive data during the measurement period; that is, the user rate is 0 at that time. Consequently, this contributes to a slight reduction in the downlink and uplink rates of the whole day after averaging.

In summary, after enabling the periodic 4G/5G inter-system measurement, a minor increase was observed in the 5G drop ratio. However, there was no obvious effect on the RRC establishment success ratio. Moreover, the handover success ratio of the UE increased. Nevertheless, there was a slight decrease in both the downlink and uplink data rates.

Periodic 4G/5G inter-system measurements had a certain impact on the network, leading to a slight increase in the short-term 5G drop ratio of a small number of users and a slight decrease in uplink and downlink rates for these users. However, acquiring 4G and 5G inner-system MRs is a conventional analysis method for 4G and 5G networks, respectively. The additional requirement of the new algorithm for the actual network is to enable both 4G inter-system and 5G inner-system reporting functions at the same time. Therefore, for scenarios with network analysis requirements, there is no additional impact. Additionally, the impact of this algorithm on user experience is limited to the network optimization stage, providing a reference for subsequent 5G construction planning and improving all user experiences. It is worthwhile to accept a small degradation in short-term user experience for an improvement in all user experiences. Finally, whether to enable MR acquisition is manually controllable at any time. Operators can proactively regulate when and where to conduct acquisition and analysis. In future data acquisition, a relatively short sampling time can be fixed.

5. Conclusions

In this study, we conducted an in-depth investigation into the optimization algorithm for 5G coverage calculation based on multi-system/multi-frequency collaboration. All results were obtained based on analysis of data acquired from commercial 4G and 5G SA networks. We present practical test results that confirm that this problem exists, both quantifying and locating it. This finding is crucial for the optimal design of MR-based coverage estimation algorithms. Based on this, we propose an achievable optimization algorithm for coverage evaluation and give a concrete implementation and extension scheme. Finally, we conducted a field test of the optimization algorithms by building a test environment based on mainstream equipment vendors in the first actual commercial scale of the largest 5G SA network. The optimized algorithm was proven to be effective in detecting more weak coverage areas.

However, because the implementation of the new algorithm needs to enable periodic inter-system measurements, it leads to some limitations in its applications: Enabling periodic inter-system measurements requires that the eNodeB and gNodeB belong to the same operator and manufacturer, which brings some resource overhead and risks of degradation of some user experiences. From the perspectives of users, since the 4G/5G inter-system measurement is periodically reported by a small number of random users in a certain area, it only causes a momentary rate drop for the single user. Therefore, it does not cause significant loss to the overall experience. For operators, the focus is to find and fix the 5G blinding coverage to improve all the user experiences. The acquisition of MRs is carried out to periodically randomize a few users at a certain time and in a specific area. Therefore, we believe that it is worthwhile for operators to take a short-term risk of user experience degradation in exchange for improving all users' experiences from a holistic point of view. The global network industry can enable the periodic inter-system measurement function on demand based on the actual network conditions to ensure that the user experience meets expectations.

Our results not only significantly contribute to enhancing the optimization of traditional network coverage evaluation, but are also highly generalizable and applicable, and can be extended as a key enabler for most of the AI-based automation use cases, including automatic detection of coverage gaps, identification of weak coverage grids, etc. Additionally, as the method proposed in this study obtains a more realistic 5G coverage, it can be used to guide network configuration and enhance signal quality in weak coverage areas. However, it's important to note that network configuration adjustments and adding base station operations may generate additional interference, which can serve as a new exploration direction in the future. Furthermore, the tradeoff between overhead and accuracy deserves further discussion, which can be explored and analyzed as a focus of future studies. Another interesting direction can be extended to deployments at 6G and beyond, e.g., in the transmission of millimeter waves. Since the propagation conditions in the millimeter-wave bands are very different compared to the bands below 6 GHz, the problem of accurate coverage evaluation is crucial in next-generation millimeter-wave (mmWave) networks. These are promising directions for future research to continue and expand upon this study.

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