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Research on 5G NR Millimeter Wave Beam Management: A Systematic Support Analysis Based on Waveform, Reference Signal and Channel Coding

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Abstract. As 5G mobile communication systems expand into millimeter-wave bands, their enormous continuous bandwidth potential provides a crucial physical foundation for improving network capacity and peak data rates. However, the inherent high path loss, susceptibility to obstruction, and rapid time-varying characteristics of millimeter-wave signals pose a significant challenge to achieving stable and reliable wireless connections. Against this backdrop, efficient beam management technology has become a core enabler for overcoming these physical layer deficiencies and unlocking the potential of millimeter-wave communication. This paper focuses on the 5G New Radio(5G NR) standard and aims to systematically clarify how fundamental physical layer technologies directly determine and optimize the performance of higher-level beam management processes. First, it analyzes flexible waveform parameter sets, reference signal design, and advanced channel coding schemes to enhance control channel reliability for beam management. Then, it delves into how these physical layer mechanisms specifically empower key protocol processes such as initial beam scanning and access, connected-state beam tracking and refinement, and beam failure detection and recovery. This study concludes that the construction of an efficient and robust millimeter-wave beam management system relies on in-depth integration of physical layer signal processing technologies and upper-layer protocol state machines.

Keywords: 5G NR, millimeter wave, beam management, channel coding, reference signal

1. Introduction

The fifth-generation mobile communication systems are accelerating its expansion into the millimeter wave bands to utilize its rich spectrum resources to meet the future network requirements for extremely-high data rates and ultra-low latency. However, the inherent physical layer defects of millimeter wave signals, such as high path loss, susceptibility to blockage, and rapid fading, seriously restrict its coverage and connection reliability. For this reason, large-scale multiple input multiple output and beamforming technology have become key, and efficient beam management is the core to realize its potential [1]. Beam management runs through the entire lifecycle of user equipment from search and access to service hold, and its performance directly affects the actual experience and network efficiency of millimeter wave systems.

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Current research has yielded significant results in physical layer technologies and higher-level protocols, but most works treat these two as relatively independent modules, lacking a systematic cross-layer analytical framework that spans from physical layer foundations to higher-level processes. This paper aims to fill this gap. It first deconstructs the key physical layer technologies supporting beam management. It then analyzes how these technologies are invoked and shape higher-level management processes. Finally, it identifies key performance trade-offs and design principles through comparative analysis, thus providing a comprehensive theoretical and practical framework for the optimization and deployment of efficient, robust mmWave beam management systems.

2. Key technologies of 5G NR physical layer supporting beam management

Beam management is not an isolated high-level protocol process; its effectiveness fundamentally depends on the infrastructure and capabilities provided by the underlying physical layer. This chapter systematically deconstructs the three key physical layer technologies supporting the 5G NR millimeter-wave beam management system: flexible parameter set waveforms, reference signal design optimized for beam management, and advanced channel coding schemes to ensure the reliability of control signaling.

2.1. Waveform and frame structure of flexible parameter sets

A core innovation of the 5G NR physical layer lies in the adoption of scalable and flexible numerologies. The parameter set is defined by the subcarrier spacing and the cyclic prefix. Unlike the fixed 15kHz subcarrier spacing of 4G LTE, 5G NR allows the SCS to be extended many times over (e.g., 60kHz or 120kHz is often used in the millimeter wave band) [2]. Such flexible numerology design delivers profound implications for millimeter wave beam management performance. First, the larger subcarrier spacing directly reduces the duration of OFDM symbols, thereby shortening the time required for a complete beam scan. This helps reduce initial access delay and beam tracking response time, which is crucial for meeting the latency requirements of URLLC services. Furthermore, the wider SCS also improves the system's robustness to phase noise in the millimeter-wave high-frequency band, ensuring high-precision phase control for beamforming. Meanwhile, the flexible frame structure supports finer time-granular reference signal insertion, facilitating efficient dynamic scheduling between beam measurement and data transmission. Therefore, the selection of the parameter set is the primary physical layer trade-off the system makes between latency performance, phase noise tolerance, and scheduling flexibility.

2.2. Reference signal design for beam management

Reference signals are used for channel detection and quality measurement in beam management systems. 5G NR has designed specialized, functionally separated sets of reference signals for different stages of beam management.

2.2.1. Synchronization signal block and initial beam scan

The synchronization signal block(SSB) is the core reference signal in the initial access phase, comprising the primary synchronization signal, the auxiliary synchronization signal and the physical broadcast channel. The SSB is transmitted periodically in the form of burst sets, and each SSB is transmitted using a specific analog beam. This mechanism enables the gNB to cover the entire cell

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through spatial scanning. The design of the SSB directly determines the scanning granularity, discovery delay and coverage performance of the initial beam management [3].

2.2.2. Channel state information reference signal and beam refinement

After the establishment of RRC connection, the system proceeds to a more refined beam management phase, where channel state information reference signals(CSI-RS) serve as the core enabling signals. Unlike the broadcast synchronization signal block, CSI-RS is user-specific and highly configurable. The network can configure periodic, non-periodic or semi-persistent CSI-RS resources for user equipment(UE) for beam measurement. Such flexibility is manifested in three aspects. First, the antenna port quantity is flexibly configurable, supporting settings ranging from single-port to multi-port deployment. Second, the density and pattern of the time and frequency domain can be configured according to requirements, realizing more refined spatial channel detection than SSB. Third, this signal is closely bound to the beam failure detection mechanism. Through CSI-RS-based measurement, the UE can report more accurate channel state information to the base station, thereby driving the beam refinement and beam tracking process in the connected state [4].

2.3. Coding schemes to enhance control channel reliability

In the rapidly changing channel environment of millimeter waves, all commands in the beam management process rely on reliable transmission through the control channel. Therefore, 5G NR introduces a more robust channel coding scheme to ensure its robustness.

For downlink control information(DCI) carrying critical scheduling and real-time beam indication, 5G NR uses polar codes with excellent performance under short code length. By contrast, LDPC codes with strong cspability for large-block payload processing are configured for the physical downlink shared channel(PDSCH) delivering upper-layer beam -management-related configuration signaling. In millimeter wave fast time-varying channels, the transmission reliability of signaling such as beam switching indication is directly related to the continuity of the management process. The introduction of these two types of coding significantly reduces the risk of process interruption due to signaling errors [5].

In summary, the flexible parameter set provides a time-frequency framework adapted to millimeter-wave beam management, the user-specific CSI-RS constitutes a tool set for spatial sensing and measurement, and enhanced channel coding ensures reliable transmission of management commands. These three elements work together to form the physical layer foundation supporting efficient and robust beam management operations.

3. Initial beam scanning and access mechanism analysis

Initial beam scanning and access is the first step in establishing a connection between user equipment and the network, and it is also a key link that determines the user experience [6]. In the millimeter wave band, due to the huge path loss and extremely narrow beamwidth, the traditional omnidirectional broadcast access method is no longer applicable, and instead, a directional access process based on beam scanning is adopted.

3.1. Scanning and discovery process based on synchronization signal blocks

In 5G NR millimeter-wave systems, the initial access begins with the scanning and discovery of SSBs. The period of the SSB burst set, the number of internal SSBs, and the beam pattern of each SSB are key parameters in network planning, directly determining the cell's coverage, scanning latency, and resource overhead.

On the UE side, the initial access process begins with beam search. The UE scans the receive beam in all possible directions, attempting to detect and decode the SSB from the gNB. The UE completes symbol timing synchronization and cell ID identification by capturing the PSS and SSS, and then decodes the PBCH to obtain the most basic system information (MIB) [7]. More importantly, the UE measures the RSRP of each received SSB during the scan. By comparing RSRP values across multiple SSBs, the UE identifies the optimal downlink receive beam and corresponding uplink transmit beam.

This "scan-measure-select" process is essentially a rough "handshake" between the UE and gNB in the spatial dimension. Narrow beams can provide higher antenna gain to overcome path loss, but excessively narrow beams may lead to coverage gaps. Therefore, the selection of SSB beamwidth is a balance between link budget and coverage continuity.

3.2. Beam measurement, reporting and random access procedures

After the UE successfully detects and selects the optimal SSB beam, the access process enters the second stage, namely beam information reporting and random access. The goal of this stage is to announce the existence of the UE to the network and establish an initial RRC connection based on the discovered optimal beam [8].

Before initiating random access, the UE has determined an optimal SSB index based on the RSRP of the measured SSB. In contention-based random access, the UE selects the physical random access channel(PRACH) resource corresponding tothe optimal SSB for preamble transmission. This means that the transmission of Msg1 itself already carries the beam information selected by the UE - by detecting the preamble from a certain PRACH resource, the gNB can infer the approximate beam direction of the UE, and thus can use the corresponding beam to send the random access response [6].

After the gNB allocates uplink resources to the UE in the random access response, the UE can carry a more detailed beam measurement report in Msg3, providing input for subsequent fine-grained beam management. The entire random access process is deeply coupled with beam management: the UE implicitly transmits beam direction information through PRACH resource selection, and the gNB forms a directional response beam accordingly.

4. Connected-state beam tracking and robustness enhancement mechanisms

Millimeter wave channels change rapidly and are prone to blockage. User movement, object obstruction, or even slight rotation of handheld devices can cause rapid changes in the optimal beam direction or even link interruption [9]. Therefore, an efficient and robust connection-state beam tracking and recovery mechanism is the key to ensuring that 5G millimeter wave systems continuously provide highly reliable and low-latency services.

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4.1. Beam measurement and dynamic refinement based on CSI-RS and SRS

The beam pair links determined during the initial access phase are only preliminary. In the connected state, the network continuously monitors and dynamically optimizes the beampair links by periodically or non-periodically configuring CSI-RS and SRS.

Transmitted by the gNB, CSI-RS primarily supports downlink beam measurement and refinement. The network can configure multiple CSI-RS resource sets for the UE, and each resource set is associated with one or more transmit beams. The UE measures the reception quality of these CSI-RS and reports the CSI report to the gNB [10]. Based on this report, the gNB can dynamically switch the transmit beam of the PDSCH from the wider SSB beam to the narrower and more precise CSI-RS beam, thereby obtaining higher beamforming gain.

The sounding reference signal(SRS) is transmitted by the UE and used for uplink beam measurement and optimization. The gNB (Ground-by-Network Controller) evaluates the uplink channel quality by receiving SRS transmitted by the UE in different uplink beam directions and selects the optimal uplink transmit beam for the UE accordingly. In TDD systems with channel reciprocity, the gNB can also infer the downlink channel state based on uplink SRS measurements, thereby assisting in downlink beam selection. This significantly reduces the signaling overhead and latency of beam management.

4.2. Beam failure detection and recovery process

Beam failure detection is based on continuous monitoring of the downlink control channel by the user equipment. If repeated PDCCH decoding failures happen on the active serving beam, a beam failure instance will be counted. Once the accumulated count goes above the preset threshold within the assessment window, the system flags a beam failure and starts the corresponding recovery flow.

This process aims to quickly rebuild the link: the user equipment first measures the preset candidate beam reference signal, selects the optimal new beam, and then sends a recovery request containing the new beam index to the base station via the uplink control channel or dedicated random access resources. Upon receiving the request, the base station responds in the new beam direction and reconfigures link resources, thus completing the recovery. The success rate and timeliness of BFR directly determine the service reliability of the system in a dynamic congestion environment.

4.3. Beam management and robustness assurance of control channels

PDCCH transmission binds to different control resource sets. Each CORESET defines its PDCCH transmit beam through the corresponding TCI state. To improve robustness, NR introduces a dedicated BFR-CORESET, which typically uses a wider or more robust beam. After triggering beam failure recovery, the user equipment can reliably receive the network recovery response by listening to the BFR-CORESET [11].

Another important mechanism to enhance the robustness of the control channel is beam scanning and repetition. For broadcast or multicast control information, or for UEs located at the cell edge, the gNB can repeatedly transmit the same DCI in multiple beam directions, trading spatial diversity for coverage reliability.This practice raises control channel resource costs but effectively lifts reception reliability of key control signals under poor channel environments.

In summary, connected beam management is a three-dimensional defense system consisting of dynamic measurement refinement, fast failure recovery, and robust control signaling, which together ensure that 5G millimeter wave systems can still provide continuous, reliable, and high-performance services in highly dynamic and challenging wireless environments.

5. Conclusion

This paper focuses on 5G NR millimeter-wave beam management, employing a systems analysis approach to reveal the profound coupling between key physical layer technologies and high-level management processes. The study indicates that beam management is central to realizing the potential of millimeter waves, and its effectiveness fundamentally depends on the underlying physical layer design. Flexible parameter sets, dedicated reference signals, and enhanced channel coding collectively form the basis for the system's sensing, execution, and propagation. On the protocol layer, the whole workflow covers SSB-driven initial access, as well as CSI-RS/SRS-based beam refinement, continuous tracking and fast beam failure recovery under connected mode. Such multi-stage management architecture mitigates dynamic blocking and maintains stable wireless links [12]. This paper clarifies the transmission mechanism and trade-off relationship from physical layer parameters to management process efficiency and then to system performance by linking physical layer design and protocol processes, and provides a framework for system design and optimization. This study mainly focuses on the principle and qualitative analysis based on standards. It is still insufficient in terms of accurate quantitative simulation and in-depth exploration of complex scenarios, which also points to the future direction [13]. First, the deep integration of artificial intelligence and beam management is an inevitable trend to break through the current paradigm bottleneck.Deep learning enables proactive beam switching via channel and obstacle prediction, while reinforcement learning optimizes measurement, feedback and recovery policies to achieve intelligent cross-layer resource allocation [14, 15]. Second, facing the integration of communication, sensing and computing in 6G, the beam management paradigm will undergo a fundamental change. It is necessary to explore the integrated waveform and beam design of communication-sensing, study the distributed beam management of multi-node collaboration, and empower future 6G applications [16].

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