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Research on Millimeter-Wave Communication Beam Alignment Method Assisted by Electromagnetic Sensing

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Abstract: *Millimeter-wave communication has the advantages of large bandwidth and high transmission rate, and is one of the core technologies for 5G-A and 6G mobile communications. Millimeter-wave signals feature short wavelengths and weak diffraction capability. Their transmission is vulnerable to occlusion and interference in mobile scenes. The accuracy and efficiency of beam alignment directly determine overall communication system performance. Traditional millimeter-wave beam alignment methods realize matching through full-domain beam scanning. They have simple operation workflows but require long scanning times and consume massive computing resources. They are prone to beam misalignment and communication interruptions in dynamic communication scenarios. This paper proposes a millimeter-wave communication beam alignment method assisted by electromagnetic sensing. It collects electromagnetic environment and terminal position information in advance to provide prior data support for beam alignment. It narrows the beam-scanning range, reduces invalid scanning steps, and improves beam-alignment speed and accuracy. A simulation test platform is built to compare the performance difference between the traditional beam alignment method and the proposed method. Test results show that the proposed method effectively reduces beam alignment delay, cuts system resource overhead, and improves the stability of millimeter-wave communication in dynamic scenarios.*

Keywords: *Millimeter-Wave Communication; Electromagnetic Sensing; Beam Alignment; Dynamic Scenarios; Communication Delay*

1. Introduction

The continuous upgrading of mobile communication technology raises user requirements for communication rate, communication delay, and communication stability. Millimeter-wave communication has abundant spectrum resources and far higher transmission bandwidth than traditional microwave communication. It can satisfy high-speed communication demands such as high-definition video transmission, massive data interaction for the Internet of Things and low-altitude communication, and has become a key technical support for new-generation mobile communication [1]. Millimeter-wave signals have obvious physical drawbacks. Their wavelengths remain at the millimeter scale, penetration performance is poor, and obstacles including buildings, human bodies,, and vehicles easily block them. Millimeter-wave communication widely adopts narrow-beam transmission. Narrow beams have small coverage, and slight terminal movement will cause beam offset and further trigger beam misalignment [2].

Beam alignment is a core procedure in millimeter-wave communication for establishing links and transmitting data stably. Traditional millimeter-wave beam alignment methods mainly adopt the traversal-scanning mechanism. Communication devices activate all candidate beams sequentially and select optimal beam pairs by detecting received signal strength to complete beam alignment [3]. Without relying on prior scenario information, these methods apply to simple static communication scenarios, but they have prominent defects. Full-domain traversal scanning consumes plenty of time-slot resources and brings long beam alignment delay. Under scenarios with high-speed terminal movement and dynamically changing obstacles, the scanning speed of traditional methods cannot keep pace with scenario variations. Beam alignment accuracy drops sharply, frequent beam realignment occurs, and system redundant overhead increases [4].

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To address the drawbacks of traditional beam alignment methods, the industry has begun researching sensing-assisted intelligent beam alignment technologies. Electromagnetic sensing technology can collect real-time electromagnetic signal features, channel states and target terminal orientations in communication space, and accurately capture dynamic scenario variations [5]. Prior information from electromagnetic sensing provides directional references for millimeter-wave beam alignment, reduces blind scanning, and fundamentally improves beam alignment efficiency. Most existing research on sensing-assisted beam alignment focuses on vision-based and radar-based sensing. Specialized studies on electromagnetic sensing are limited, and the integration mechanism between electromagnetic sensing and millimeter-wave beam alignment remains imperfect [6].

This paper focuses on the integrated application of electromagnetic sensing and millimeter-wave beam alignment and proposes a complete, optimized beam alignment method. First, this paper analyzes the core principles and existing problems of millimeter-wave beam alignment and identifies performance weaknesses of conventional technologies under static and dynamic scenarios. Leveraging the scenario adaptability of electromagnetic sensing, this paper constructs an electromagnetic-sensing data collection and feature-extraction model, removes redundant noise from raw sensing data, and accurately extracts dynamic transmission features of communication channels. Meanwhile, this paper establishes a standardized mapping between sensing information and beam parameters, breaks the irregular, unguided scanning mode of traditional beam scanning, and finally enables fast, accurate, low-power beam alignment. Simulation experiments under multiple working conditions verify the effectiveness of the proposed method. Performance analysis covers three core dimensions: delay, alignment success rate, and resource overhead. This research provides new technical ideas for beam optimization in dynamic millimeter-wave scenarios and offers theoretical references for the practical deployment of integrated sensing and communication technology.

Against the backdrop of ongoing 6G technology iteration, integrated sensing and communication has turned into a core development direction for wireless communication. Conventional communication devices only undertake data-transmission tasks, leading to low utilization of hardware resources. Electromagnetic sensing enables passive sensing using communication antenna arrays. It does not require extra sensing hardware such as radars and cameras. Hardware multiplexing of communication and sensing functions can be achieved, which greatly reduces deployment costs and equipment volume for base stations and terminals. Most research on sensing-assisted beam alignment currently focuses on visual sensing and millimeter-wave radar sensing. Visual sensing is vulnerable to illumination, rain, snow, and occlusions, while radar sensing has high hardware power consumption. Neither sensing mode can directly obtain core transmission parameters of communication channels, so the matching degree between sensing data and beam communication is low. Electromagnetic sensing directly extracts features from communication electromagnetic signals. Its sensing data are highly compatible with millimeter-wave communication links, can accurately reflect real-time beam transmission status, and possess irreplaceable strengths under complex dynamic scenarios. Nevertheless, the integration system combining electromagnetic sensing and millimeter-wave beam alignment is immature. Standardized feature-extraction algorithms and beam-screening mechanisms are lacking, which are core problems this paper addresses.

2. Basic Theories and Existing Problems of Millimeter-Wave Beam Alignment

2.1 Beam Transmission Characteristics of Millimeter-Wave Communication

Millimeter waves cover the frequency range of 30 GHz-300 GHz, with corresponding wavelengths from 1 mm to 10 mm. The millimeter-wave spectrum contains abundant idle resources and does not require complicated spectrum planning. Single-channel transmission bandwidth can reach the GHz level and support Gbit/s high-speed data transmission [7]. Millimeter-wave communication systems commonly adopt large-scale antenna-array technology. Beam forming concentrates signal energy within narrow beams, improving directivity and transmission gain.

Narrow-beam transmission enables high-speed millimeter-wave communication but also creates beam-alignment challenges. Narrow beams have extremely small coverage angles, normally ranging from several degrees to more than ten degrees. Transmit and receive beams must be strictly aligned to guarantee valid signal transmission. Beam-alignment accuracy directly determines communication-link gain. Even small angular deviations can cause severe signal attenuation. Terminal displacement, rotation, or dynamic obstacles can significantly alter beam transmission paths. Originally well-matched beam pairs can suffer significant offset; the communication link signal strength drops rapidly, and

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communication may even be completely interrupted.

Beyond terminal movement and physical occlusion, millimeter-wave propagation environments also significantly affect beam-alignment performance. Millimeter-wave signals suffer prominent atmospheric loss, rain attenuation, and multipath fading. Under complex outdoor weather conditions, electromagnetic propagation environments change rapidly, and fixed beam-matching parameters fail to adapt to real-time channel states. Traditional beam-alignment methods focus only on beam-angle matching and ignore implicit factors such as channel loss and multipath propagation. Even if beam angles align, communication quality may still be unsatisfactory. This problem is especially pronounced in high-speed vehicular and low-altitude UAV communication scenarios, and it is a major reason traditional traversal beam-alignment technology cannot be deployed at scale [8].

2.2 Working Mechanism of Traditional Beam Alignment

Current commercial millimeter-wave communication systems mainly adopt codebook-based beam traversal alignment. The system pre-stores fixed beam codebooks containing multiple beam vectors with different angles and gains. Beam alignment consists of three basic steps. The first step is beam scanning: base stations and terminals activate all beams in the codebook in preset order for signal transmission and reception. The second step is signal detection: devices detect parameters such as received signal strength and signal-to-noise ratio for each beam. The third step is beam matching: the system selects the beam pair with optimal parameters to serve as the working beam for formal communication and completes beam alignment [9].

The traditional traversal-scanning method has low technical barriers and does not require complex algorithm computation. It can satisfy basic communication demands under static scenarios. However, its severe resource loss makes it poorly suited for commercial high-speed communication scenarios. Beam codebooks contain a large number of beams. Full-domain scanning requires signal transmission, reception, and detection for every beam and consumes substantial communication time slots. Time-slot resources for millimeter-wave communication are precious. When many time slots are occupied by invalid scanning, effective resources for user-data transmission shrink, and system communication throughput decreases. Single beam-alignment delay is high. In high-speed mobile scenarios, terminal positions have already changed by the time one full-domain scanning round finishes. The resulting optimal beams quickly become invalid, and the alignment success rate drops significantly.

Meanwhile, frequent full-domain scanning increases computing load and radio-frequency power consumption, reducing the operating efficiency and service life of millimeter-wave communication systems. Under continuous dynamic scenarios, traditional methods need uninterrupted realignment. Repeated scanning and matching generate massive redundant system data, occupy device storage resources, and further aggravate operating burdens. For low-power devices such as lightweight IoT terminals and vehicular terminals, power-consumption defects of traditional beam-alignment methods severely limit equipment service life and working stability, and cannot meet long-term, stable high-speed communication requirements.

2.3 Core Defects of Existing Beam-Alignment Technologies

Beyond traditional traversal-scanning methods, some existing optimization algorithms improve alignment efficiency by simplifying codebooks and optimizing scanning sequences, but their gains are limited. First, existing methods lack scenario-sensing capability. They cannot predict terminal positions and beam-transmission paths in advance and still involve numerous invalid scanning operations. Second, they adapt poorly to dynamic scenarios and cannot quickly cope with complex conditions such as variable occlusions and high-speed terminal movement. Third, beam-tracking performance is poor. Once beam misalignment occurs, full-domain scanning must restart, leading to high system overhead [10].

Sensing-assisted technology can effectively compensate for the above-mentioned defects and has become a core direction for optimizing millimeter-wave beam-alignment performance. Common auxiliary sensing technologies include vision sensing, LiDAR sensing, millimeter-wave radar sensing, and electromagnetic sensing, each with distinct scenario adaptability. Vision sensing identifies terminal positions and occlusions via image acquisition. It is low-cost and provides good visualization, but it fully depends on illumination conditions. Its accuracy declines sharply at night, in fog, dust, or strong-light environments, so it cannot work round-the-clock. LiDAR sensing delivers high positioning accuracy but requires expensive hardware and is susceptible to thin occlusions with poor penetration.

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Millimeter-wave radar sensing offers strong anti-interference capability but requires high hardware power consumption. Its sensing data reflect only spatial positions, not channel-transmission quality.

Electromagnetic sensing can directly acquire real-time channel states and accurately capture dynamic beam-transmission features. Compared with other sensing approaches, electromagnetic sensing is immune to light, weather, and occlusions and supports all-weather, full-scenario operation. Moreover, it can reuse communication antenna hardware without extra deployment, showing prominent advantages in hardware cost and power consumption. Its sensing data are highly consistent with beam-communication requirements. Therefore, this paper optimizes beam-alignment workflows based on electromagnetic-sensing technology to address the low efficiency, high power consumption, and poor adaptability of traditional methods.

3. Design of Electromagnetic-Sensing-Assisted Beam-Alignment Method

3.1 Overall Architecture of the Proposed Method

The electromagnetic-sensing-assisted beam-alignment method proposed in this paper includes four core modules: electromagnetic-information acquisition module, feature-extraction module, beam-parameter mapping module, and precise-alignment-and-tracking module. The overall workflow is as follows: the system collects real-time electromagnetic-signal data of communication areas via electromagnetic-sensing devices, extracts core features such as channel gain, signal arrival angle and path loss, establishes mapping relations between sensing features and beam-codebook parameters, screens high-probability optimal beam subsets, and performs precise scanning and matching only for beams within subsets to finish beam alignment. Real-time beam-status tracking and dynamic optimization adjustment are realized simultaneously.

This architecture abandons the traditional full-domain scanning pattern. Prior information from electromagnetic sensing narrows scanning ranges and greatly reduces invalid operations and time-slot consumption. The four core modules operate in series with real-time data exchange, ensuring coherence and efficiency throughout the beam-alignment process. The electromagnetic-information acquisition module provides raw-data support for the whole method; the feature-extraction module performs data purification and core-parameter mining; the beam-parameter mapping module enables accurate matching between sensing data and communication beams; the precise-alignment-and-tracking module performs final beam matching and dynamic optimization.

The proposed method has a simple architecture and low computational complexity. It adopts lightweight data computation without complicated deep-learning models or large-scale matrix operations. It can be deployed on ordinary commercial millimeter-wave communication chips and is compatible with various millimeter-wave communication equipment such as base stations, vehicular terminals, and high-speed IoT terminals. In addition, the architecture enjoys favorable expandability. Multi-dimensional data modules such as temperature sensing and position sensing can be added later to implement multi-sensing-fusion beam alignment and further boost performance under extremely complex scenarios.

3.2 Electromagnetic-Sensing-Information Collection and Feature Extraction

The electromagnetic-sensing module constitutes the core foundation of the proposed method. Its main function is to collect electromagnetic-environment data in real time for communication scenarios. Antenna arrays of millimeter-wave communication equipment undertake both communication and sensing tasks. No extra hardware installation is needed, which reduces system deployment costs. During communication intervals, the equipment collects spatial electromagnetic signals and continuously obtains key data, including channel-state information, signal arrival angle, launch angle, path loss, and multipath-propagation features.

Raw electromagnetic-sensing data contain noise, interference, and high redundancy and cannot be directly used for beam-parameter matching. Electromagnetic clutter in communication environments, background noise of radio-frequency circuits, and external-signal interference will cause abnormal fluctuations in raw collected data. Direct utilization of raw data for beam matching will lead to matching deviation and wrong beam selection. This paper uses a mean-filtering algorithm to preprocess the raw data. Mean values are calculated from consecutive multi-frame sensing data to eliminate abnormal data induced by environmental noise and equipment errors while retaining valid

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channel-feature parameters.

After preprocessing, the system extracts five core indicators reflecting beam-transmission characteristics: channel gain, signal arrival angle, path loss, multipath delay, and signal-to-noise ratio, and builds a standardized electromagnetic-feature dataset. The dataset updates in real time at fixed time frames, precisely recording electromagnetic-feature differences brought by dynamic scenario changes and terminal movement. Each sensing data set ensures real-time performance and validity, provides reliable data support for subsequent beam screening and parameter matching, and improves beam-alignment accuracy at the source.

3.3 Beam-Subset Screening and Precise Alignment

Unlike traditional methods that traverse all beam codebooks, the proposed method performs beam-subset screening through electromagnetic-sensing features and greatly reduces scanning ranges. The system correlates and matches extracted electromagnetic features with angle and gain parameters of beam codebooks. Beams at different angles correspond to fixed electromagnetic-propagation rules. Based on real-time arrival-angle and path-loss data, the system locks beam ranges with potentially optimal communication performance and eliminates invalid beams with extremely low matching degrees.

After beam-subset screening, the system performs precise scanning and signal detection only for a small number of candidate beams, replacing the inefficient full-domain traversal pattern of traditional approaches. The system detects communication parameters of each candidate beam one-by-one, mainly comparing core indicators such as signal-to-noise ratio, transmission rate, channel stability, and path loss. The system selects optimal beam pairs via comprehensive weighted scoring to complete precise alignment. This approach converts full-domain scanning into short-range precise scanning, cuts over 80% of invalid scanning time slots, and greatly reduces computational resource consumption and radio-frequency power consumption.

Once beam alignment finishes, the system does not terminate electromagnetic-sensing work. It continuously collects electromagnetic-sensing data and monitors beam-transmission states in real time to form a regular beam-monitoring mechanism. When small-scale continuous variations occur in electromagnetic features, the system can predict beam-offset trends in advance and fine-tune beam angles to maintain optimal matching states, avoiding complete beam misalignment caused by expanding offset. This active adjustment mode replaces traditional passive realignment operations, effectively reduces realignment frequency, further enhances communication-link stability, and lowers system overhead.

3.4 Beam-Tracking Optimization for Dynamic Scenarios

Targeting complex scenarios such as high-speed terminal movement and dynamic occlusion, this paper designs a dynamic beam-tracking-optimization mechanism. During terminal movement, electromagnetic-sensing data exhibit continuous variation. By analyzing trends in electromagnetic features, the system predicts terminal movement directions and the changing rules of beam-transmission paths. Candidate beam subsets can be adjusted in advance without waiting for beam misalignment to trigger rescanning.

Meanwhile, the system stores historical electromagnetic-sensing data and optimal beam-matching data, classifies and archives them by scenario type, terminal movement, speed, and occlusion state, and builds a lightweight scenario-feature database. The database updates iteratively during long-term operation and accumulates beam-matching rules under various working conditions. When handling communication demands under similar scenarios and terminal states, the system can directly invoke historical optimal-matching parameters, skip repeated feature-extraction and beam-screening steps, further shorten beam-alignment time, and improve communication stability under dynamic scenarios.

The database uses lightweight storage architecture and requires minimal equipment-storage resources. It fits the deployment requirements of various small- and medium-sized communication terminals. In addition, it supports adaptive iteration and can adapt to long-term scenario changes, enabling the beam-alignment algorithm to improve performance with continuous use and addressing the fixed parameters and poor self-adaptability of traditional algorithms.

ISSN 2706-655X Vol. 8, Issue 2: 128-136, DOI: 10.25236/IJFET.2026.080216

4. Simulation Experiment and Result Analysis

4.1 Simulation-Parameter Setting

This paper builds millimeter-wave communication scenarios on the MATLAB simulation platform and constructs simulation models complying with 5G-A millimeter-wave communication standards to compare core performance between the traditional traversal beam-alignment method and the proposed electromagnetic-sensing-assisted method. The simulation adopts urban short-distance communication scenarios consistent with mainstream civilian millimeter-wave application environments. Base-station height is set to 10 m and terminal height to 1.5 m, conforming to equipment-installation heights for urban streets, residential quarters, and business districts. Communication distance ranges from 10 m to 100 m, covering mainstream distances for short-range high-speed millimeter-wave communication. The working frequency band is set at 28 GHz, the core commercial millimeter-wave frequency band with mature hardware support and communication standards. An 8 × 8 large-scale antenna array is adopted, and the beam codebook contains 64 groups of candidate beams, matching parameter configurations of existing commercial millimeter-wave equipment. Two working conditions are configured: static scenarios and dynamic-mobility scenarios. Static scenarios verify basic alignment performance. Terminal movement speed under dynamic scenarios ranges from 0 km/h to 30 km/h, covering normal pedestrian and low-speed vehicle speeds. Three core test indicators are selected: beam-alignment delay, alignment success rate, and system resource overhead, to comprehensively verify algorithm efficiency and stability.

4.2 Experimental Results and Analysis

Simulation results of millimeter-wave communication under two working conditions are shown in Figure 1.

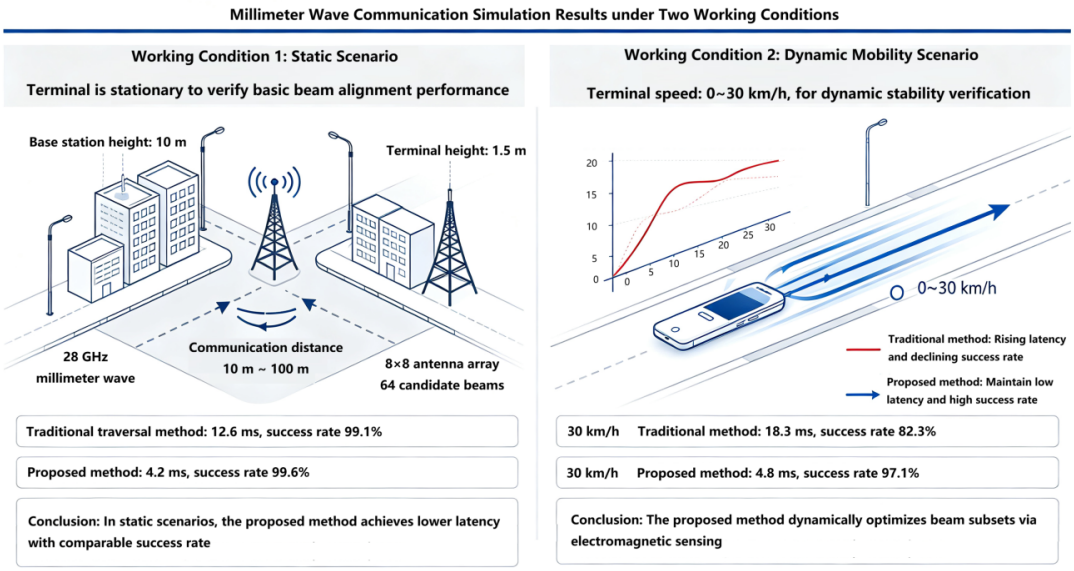


Figure 1: Simulation Results of Millimeter-Wave Communication under Two Working Conditions

This paper compares performance using two sets of simulation experiments, with specific results presented below.

ISSN 2706-655X Vol. 8, Issue 2: 128-136, DOI: 10.25236/IJFET.2026.080216

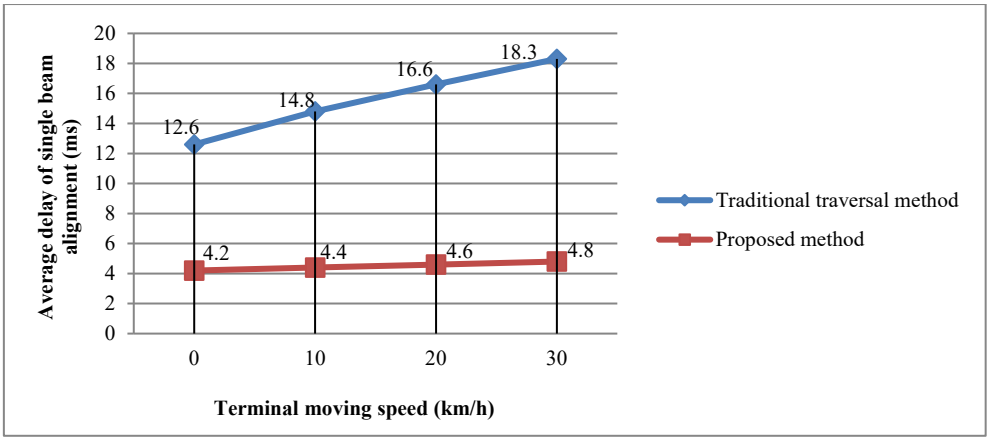


Figure 2: Comparison of Beam-Alignment Delay between Two Methods

Figure 2 illustrates variations of beam-alignment delay for the two methods under static scenarios and dynamic scenarios with different movement speeds. The horizontal axis represents terminal movement speed, and the vertical axis denotes average single beam-alignment delay. As shown in the figure, under static scenarios, the traditional traversal method's average alignment delay reaches 12.6 ms. In comparison, the proposed method achieves 4.2 ms, a 66.7 % reduction. Under dynamic scenarios, the traditional method's alignment delay continues to rise as terminal speed increases, reaching 18.3 ms at 30 km/h. The proposed method shows minimal delay fluctuation, with a delay of only 4.8 ms at 30 km/h. This is because the proposed method narrows beam-scanning ranges by relying on electromagnetic sensing, is barely affected by terminal movement speed, and can sustain low-delay alignment capability.

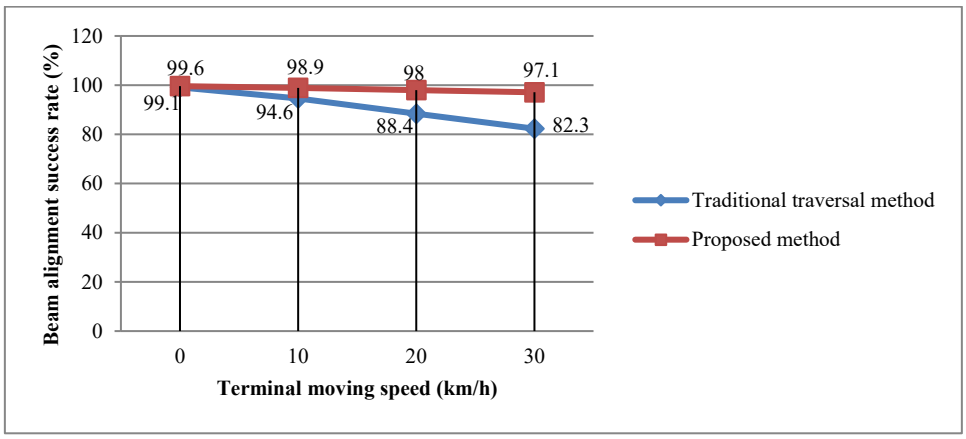


Figure 3: Comparison of Beam-Alignment Success Rate between Two Methods

Figure 3 shows variation rules of beam-alignment success rate for the two methods under different scenarios. The horizontal axis represents terminal movement speed, and the vertical axis stands for beam-alignment success rate. Under static scenarios, both methods achieve success rates above 99 % with minor performance gaps. Under dynamic scenarios, the traditional method's success rate drops sharply to 82.3 % at 30 km/h. The proposed method has a slight success-rate decline and still maintains 97.1 % at 30 km/h. The proposed method can predict scenario changes via electromagnetic sensing and dynamically optimize beam subsets, effectively improving beam-alignment stability under dynamic scenarios.

In terms of system resource overhead, the traditional method must traverse 64 beam groups. Each beam requires signal transmission, reception, detection, and computation, consuming substantial time-slot and computing resources for a single alignment. Benefiting from prior screening by electromagnetic sensing, the proposed method eliminates most invalid beams. The average number of candidate beams is only 8-12, and invalid-scanning times decrease greatly. Statistical simulation data show that the proposed method reduces system computing-resource overhead by 58.2 % compared with the traditional method. Radio-frequency working time shortens significantly, and overall equipment power consumption is effectively controlled. For battery-powered mobile terminals, reduced power consumption can effectively extend service life and enhance continuous working capacity.

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Beyond the three core indicators, this paper also compares the communication-link stability of the two methods. Under complex working conditions of 30 km/h high-speed movement and intermittent slight occlusion, the traditional method produces an average of 4.2 link fluctuations per second. It often suffers from instantaneous stuttering and packet loss. The proposed method has only 0.8 link fluctuations per second and greatly improved link stability. It can well satisfy service requirements of high-definition video transmission and real-time data interaction that demand high communication stability.

Comprehensive simulation results show that the electromagnetic-sensing-assisted beam-alignment method proposed in this paper reduces alignment delay and system resource overhead while maintaining alignment accuracy, significantly improves beam-alignment reliability under complex dynamic scenarios, and delivers better overall performance than the traditional traversal-alignment method.

5. Conclusion

To address high delay, large resource overhead, poor adaptability to dynamic scenarios, and insufficient link stability in traditional millimeter-wave beam-alignment methods, this paper proposes an electromagnetic-sensing-assisted millimeter-wave communication beam-alignment method. Relying on electromagnetic-sensing technology, the proposed method collects real-time prior information, such as electromagnetic-channel features and terminal-transmission states, for communication scenarios. The mean-filtering preprocessing algorithm cleans raw sensing data, and the method accurately extracts core channel-transmission features. The method screens optimal beam-candidate subsets through feature extraction and parameter mapping. The inefficient full-domain traversal-scanning mode of traditional methods is abandoned. Invalid beam-scanning operations are effectively reduced, and time overhead and computational power consumption for beam alignment are lowered.

Meanwhile, a beam-tracking-optimization mechanism is designed based on dynamic-variation rules of electromagnetic features. A lightweight scenario-feature database enables adaptive iterative updating of beam parameters, greatly improving beam-alignment success rate and communication stability under complex scenarios involving terminal movement, dynamic occlusion, and weather interference. Simulation-experiment results show that, compared with the traditional beam-traversal-alignment method, the proposed method significantly reduces beam-alignment delay and system-resource loss and weakens interference from dynamic scenarios on communication quality, and maintains high beam-alignment accuracy under high-speed mobile dynamic scenarios. It effectively solves core shortcomings of traditional millimeter-wave beam-alignment technology. With a simple structure, lightweight algorithm, low deployment cost, and wide-scenario adaptability, this method requires no extra hardware and can be directly adapted to existing commercial millimeter-wave communication systems. It can well meet application requirements for 5G-A and future 6G high-speed millimeter-wave communication and possesses high engineering practical value and promotion value. Follow-up researches can further integrate multi-dimensional sensing information from vision and radar, optimize beam-prediction algorithms and iteration mechanisms for scenario databases, further improve beam-alignment performance under extreme complex scenarios, and promote large-scale practical deployment of integrated sensing-and-communication technology in the millimeter-wave-communication field.

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