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Application of 5G Communication Technology in High-Precision Navigation and Positioning

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Abstract:
This paper explores the application of 5G communication technology in high-precision navigation and positioning systems. 5G, with its low latency, high bandwidth, and advanced features such as millimeter-wave communication, Massive MIMO, and edge computing, has revolutionized the accuracy and reliability of positioning systems. The study highlights the use of millimeter waves in both outdoor and indoor environments, where it provides high precision, even under challenging conditions like signal obstruction or adverse weather. Massive MIMO further enhances spectral efficiency and enables sophisticated functionalities such as multi-target tracking and relative attitude estimation, particularly in unmanned aerial vehicles (UAVs). Edge computing is identified as a critical enabler for real-time data processing, reducing latency and improving power efficiency in UAV navigation systems and emergency evacuation applications. Through a comprehensive review of these technologies, the paper discusses the potential of 5G in driving innovation in navigation systems while also addressing key challenges such as signal obstruction and power consumption. The findings underscore the transformative role of 5G in navigation and its implications for future research and industrial applications.

Keywords: 5G Communication Technology; High-Precision Navigation; Millimeter-Wave Communication; Massive Multi-Input-Multi-Output; Edge Computing

1. Introduction

5G communication technology (5th Generation Mobile Networks) is the next generation of wireless communication technology standards following 4G. 5G technology offers higher data transmission speeds and lower latency, meeting the needs of various application scenarios such as Ultra HD video, augmented reality (AR), virtual reality (VR), the Internet of Things (IoT), autonomous driving, and smart cities.

As information technology continues to develop rapidly, 5G communication technology, with its high speed, low latency, and massive connectivity, is quickly becoming a driving force for technological innovation across various industries. 5G technology can offer higher transmission rates and lower latency. 5G technology also can introduce new technologies such as millimeter-wave communication, Massive MIMO, and edge computing [1,2]. These advancements greatly enhance positioning accuracy and anti-interference capabilities, providing new possibilities for the further development of high-precision navigation and positioning systems. However, research shows that although 5G's high-frequency millimeter-wave signals offer greater bandwidth and speed, they are easily obstructed by buildings, trees, walls, and other obstacles [3]. This can lead to unstable navigation signals in urban or indoor environments, impacting the accuracy and continuity of navigation.

Therefore, this paper aims to provide researchers and practitioners with a clear perspective on how 5G technology is driving the development of high-precision navigation and positioning through a comprehensive review and analysis of existing literature. It also aims to reveal potential directions and challenges for future research. In the context of the continuous evolution of 5G technology, exploring its potential in the field of navigation and positioning not only has academic value but also provides important technical support for emerging industrial applications. Firstly, the paper will provide an overview of 5G communication technology. Then it will focus on introducing the application of millimeter waves, Massive MIMO, and edge computing in navigation and positioning systems. Finally, it will summarize the challenges and future development of 5G navigation.

1.

2. Millimeter Wave's Application in Navigation

Initially, it was mainly used for outdoor vehicle detection and distance measurement. With the growing demand for indoor positioning accuracy, researchers started exploring the potential of millimeter-wave radar in indoor environments. By extracting and analyzing reflection information from radar signals, millimeter-wave radar can achieve high-precision positioning and tracking of indoor targets. Today, millimeter-wave radar has become an important technology in indoor positioning, widely used in smart homes, autonomous driving, and medical detection. Its high precision, strong anti-interference capability, and harmlessness to the human body give millimeter-wave radar significant advantages in indoor positioning applications.

Millimeter-wave technology achieves high precision and reliability in indoor positioning through methods such as multipath propagation, TDOA, AOA, and FMCW radar.

3.

3.1 Mmultipath Propagation and Reflection Information

Yunchou Xing et al measured reflection and scattering measurements of drywall at 28, 73, and 142 GHz [4]. The results show that millimeter-wave signals in indoor environments undergo multipath propagation, where the signals reflect off walls, ceilings, furniture, and other obstacles. Millimeter-wave radar can capture these reflected signals and use the characteristics of multipath propagation for positioning. By analyzing the time delay and strength of these reflected signals, millimeter-wave systems can determine the position and movement trajectory of target objects.

Therefore, in indoor positioning, this multipath effect can be fully utilized to improve positioning accuracy by analyzing and processing these multipath signals.

3.2 Time Difference of Arrival (TDoA)

Time Difference of Arrival (TDoA) is a positioning technique used to determine the location of a signal source by measuring the time difference of the signal arriving at different receivers. TDoA is widely used in various scenarios requiring high-precision positioning, particularly in fields such as wireless communication, navigation and the Internet of Things (IoT).

This method utilizes multiple millimeter wave base stations [5]. Two base stations measure the arrival time difference of the signal emitted by the mobile station, which is then converted into the distance difference between the mobile station and the two base stations. By selecting different base stations, multiple hyperbolas can be obtained. Then their intersection point indicates the position of the mobile station. The TDOA positioning diagram is shown in Fig. 1.

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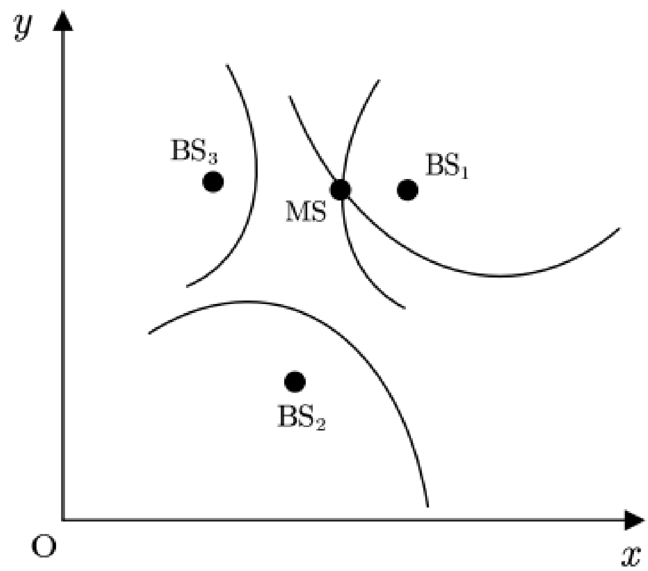

Fig. 1 TDoA positioning diagram

Assume the coordinates of base station BS1 are (x1, y1), the coordinates of base station BS2 are (x2, y2), and the coordinates of base station BS3 are (x3,y3). The coordinates of the mobile station MS to be determined are (x,y). The time difference of the signal arrival from the mobile station to base stations BS1 and BS2 is T21. Therefore, the distance difference between the mobile station and base stations BS1 and BS2 (d21) is c · T21, where c is the speed of light. Similarly, the distance difference between the mobile station and base stations BS1 and BS3 is d31. By solving the equations in (1), the coordinates of the mobile station MS can be determined.

$$\begin{cases} \sqrt{(x_2-x)^2+(y_2-y)^2}-\sqrt{(x_1-x)^2+(y_1-y)^2}=d_{21} \\ \sqrt{(x_3-x)^2+(y_3-y)^2}-\sqrt{(x_1-x)^2+(y_1-y)^2}=d_{31} \end{cases} \quad (1)$$

3.3 Angle of Arrival (AoA)

The AoA (Angle of Arrival) positioning process involves the millimeter wave base station receiving signals through an array antenna [6]. By analyzing the angular differences in the signal arrival at the antenna array, the position of the target can be determined. The AoA positioning diagram is shown in Fig. 2. This method combines spatial resolution and angular information to provide high-precision positioning results.

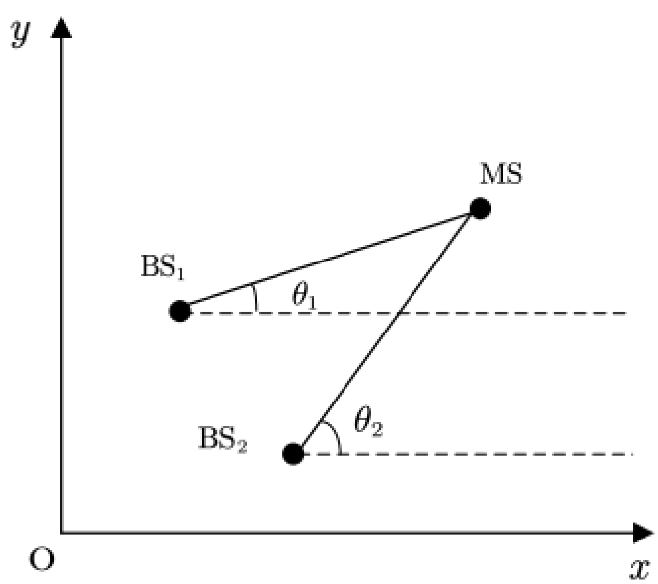

Fig. 2 AoA positioning diagram

In 5G networks, AoA technology combined with beamforming technology allows base stations to adjust the beam direction of their antenna arrays by accurately measuring the angle at which a mobile user's signal arrives [7]. This enhances signal quality and coverage, thereby improving spectral efficiency and system capacity.

2.4 Frequency Modulated Continuous Wave (FMCW) Radar

FMCW Radar is a commonly used technology for millimeter wave indoor positioning [6]. The FMCW radar system block diagram is shown in Fig. 3. FMCW radar can emit a continuously frequency-modulated signal, and then analyse the frequency difference between the transmitted and received signals (known as the Doppler shift). After that, the radar system can calculate the distance and speed of the target. FMCW radar is characterized by high accuracy, strong anti-interference capabilities and low power consumption [8]. As a result, FMCW radar plays a significant role in many fields such as autonomous driving, industrial measurement, weather monitoring and security surveillance.

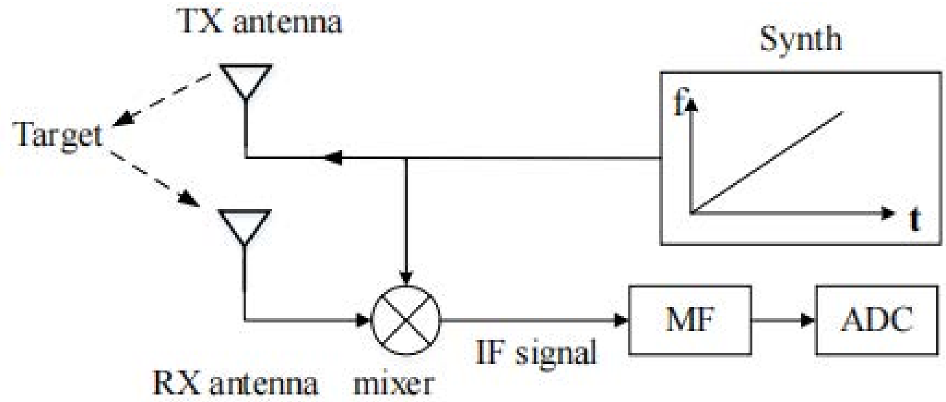

Fig. 3 FMCW radar system block diagram

3. Massive MIMO

The fundamental theory of MIMO technology was first introduced by researchers in the 1990s. During this period, research mainly focused on the theoretical models and performance analysis of MIMO systems, such as how to increase the capacity and reliability of communication systems through multiple transmit and receive antennas. The 5G communication system extensively utilizes MIMO technology, particularly Massive MIMO, which greatly enhances network capacity and data rates by deploying many antennas at the base station. The 5G network also leverages millimeter-wave frequencies, which, when combined with MIMO technology, further improves the performance of communication systems. The combination of millimeter-wave's high bandwidth and MIMO technology's high capacity lays the foundation for future wireless communications.

Massive Multi-Input-Multi-Output (M-MIMO) has been one of the most important trend points in communication in the last decade in terms of its extraordinary performance of spectral efficiency gain, which reflects its ability to utilize the channel [9]. Although it still needs improvements in power consumption and receiver saturation which is due to the received signal amplitude being larger than the receiver threshold, it has still contributed to the performance of contemporary high-user density networks to a significant degree. The basic structure of the M-MIMO system is shown in Fig. 4 below.

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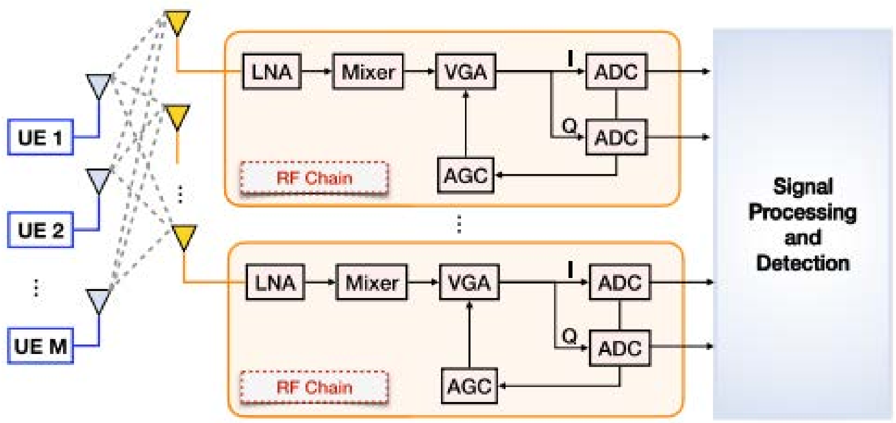

Fig. 4 The conventional architecture of the receiver of the M-MIMO system [9]

3.1 Multi-Target Tracking (MTT)

MTT is one of the core functions of modern unmanned aircraft navigation systems. With MIMO enabled, MTT allows one unmanned aircraft vehicle (UAV) to track multiple targets at the same time, while numerous UAVs will form a navigation system to improve accuracy and power efficiency. Jiahui Yang et al [10] stated in their research that with MIMO integrated into their multi-UAV radar system, the UAVs kept a balanced tracking accuracy on multiple targets through coordinated cooperation. A typical case of MTT application is shown in Fig. 5 below.

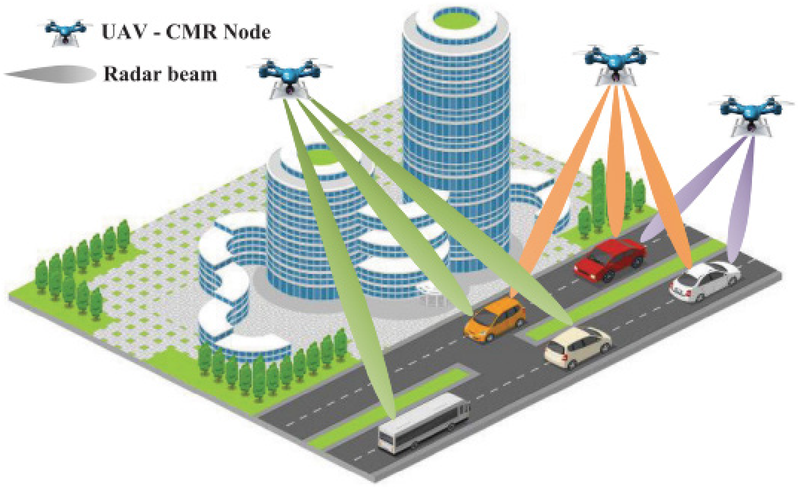

Fig. 5 Concept of multi-UAV MIMO Radar system for MTT [10]

3.2 Relative attitude estimation

MIMO also helps the UAV itself in navigation, e.g. attitude estimation. As shown in Fig. 6 below, Attitude estimation can help maintain appropriate stability and control, and it consists of 3 Degrees of Freedom (DoF), e.g. yaw, pitch and roll angles. While traditional small inertial sensors show poor performance on small UAVs and the GPS method can only provide 2 DoFs at the same time, Jon W. Wallace et al [11] conducted research on the possibility of cooperative relative attitude estimation between 2 UAVs through MIMO, in which numerous RF resources including antennas and radios are used to obtain two of the three DoFs through direction finding, while MIMO is being used to calculate the third.

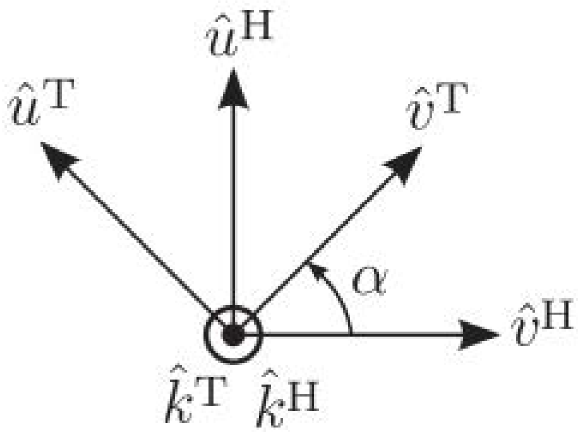

Fig. 6 The reference coordinates system of two UAVs [11]

4. Edge Computing

4.

Edge computing which is an opposite concept when compared to cloud computing, is a core feature of contemporary 5G communication networks. As shown in Fig. 7 below, in previous cases when cloud computing is used more often all the data and computations are being processed in central cloud servers, which will cause inevitable delays and unnecessary network burdens [12]. Nowadays on the Internet of Things (IoT) edge computing is being implemented as an alternative solution to perform the computation offloading, data caching and real-time data processing at the edge of the network to improve response latency, extend the battery life of the terminal devices, and as well as improve information privacy [13,14]. All of this cannot be realized without 5G service that provides low latency and high bandwidth wireless communication links.

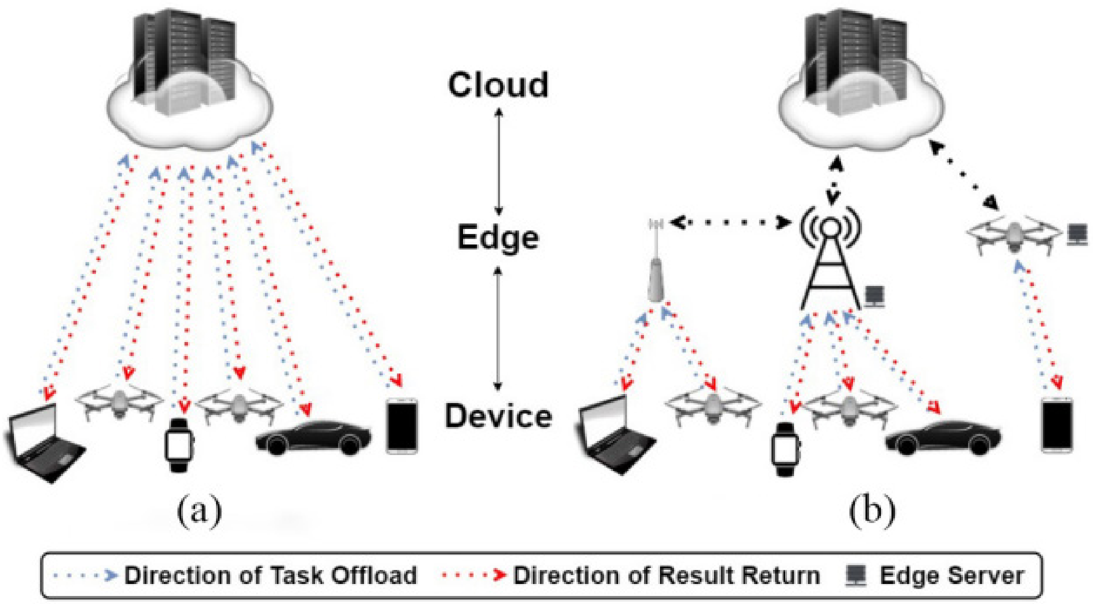

Fig. 7 The structure of cloud computing versus edge computing. [13]

4.1 Data offloading

Vision-based odometry has now become one of the core methods of UAV navigation systems, while on the contrary, the size of the UAVs limits the on-board computation power to process the image in the required time [2]. Samira Hayat et al analyzed the advantages of utilizing edge computation centres to enable real-time vision-based autonomous navigation for terminal drones. The results suggest that edge computing benefits UAV navigation by reducing processing time and terminal power consumption. This can be achieved through either partial offloading or full offloading. The processes of these two methods are shown in Fig. 8 below.

In partial offloading, the UAV itself uses its computing power to extract features from the captured images before sending these features to the edge servers for further processing. In full offloading, the original image is sent directly to the edge servers, which handle all the processing. The choice between these methods depends on the bandwidth of the communication channel between the UAV and the edge servers [2].

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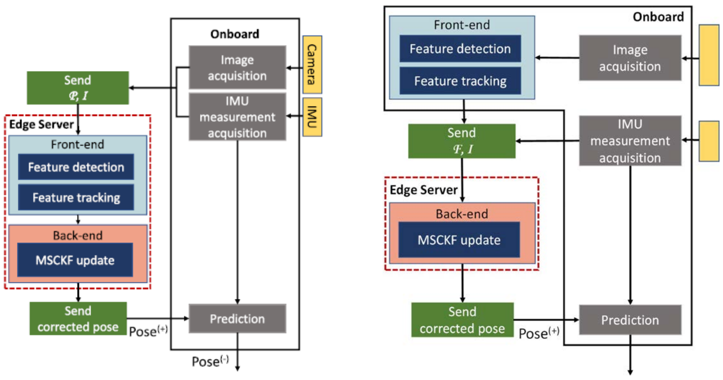

Fig. 8 The complete process of partial and full offloading of the image processing task [2]

4.2 Emergency navigation

As the public buildings, e.g. transportation junctions, hospitals etc. in cities keep growing in terms of horizontal and vertical scale, emergency evacuation navigation has become inevitable to be considered. To address this problem, Huibo Bi et al proposed a way of integrating edge computing into these facilities to improve the accuracy and latency of locating evacuees in these structures [14]. As shown in Fig. 9 below, in the building edge communication nodes with various sensors, e.g. WIFI sensors, visual sensors, temperature sensors etc. are installed in an even distribution pattern, covering the halls and important places e.g. junctions, stairs, exits etc. to give evacuees real-time evacuation instructions. With various grouping strategies in terms of healthiness, congestion and traffic balance which are all realized by the cumulative computational power provided by all the edge nodes, the percentage of survivors in the evacuation process has increased to a significant degree, while the times of congestion have decreased as well.

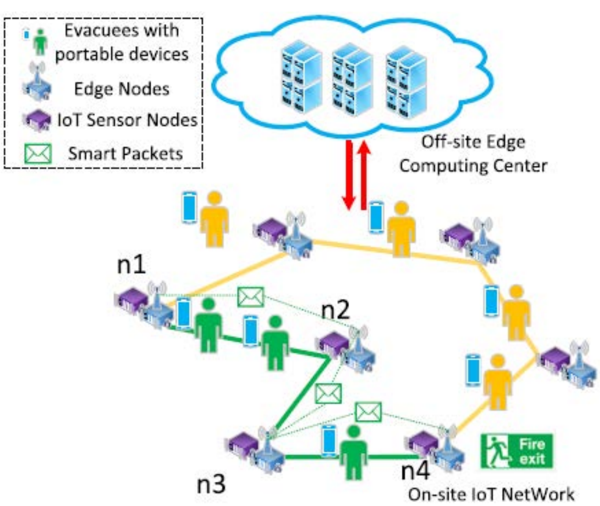

Fig. 9 The structure of the edge computing enabled emergency evacuation system [14]

5. Conclusion

The integration of 5G communication technology into high-precision navigation and positioning systems marks a transformative advancement across multiple industries.

Millimeter-wave technology stands out for its high precision and strong anti-interference capabilities, making it essential in both indoor positioning and autonomous driving. Its ability to operate effectively under adverse conditions, such as in urban canyons or inclement weather, highlights its potential for enhancing safety and operational efficiency in critical applications.

Massive MIMO technology further contributes to the precision and reliability of navigation systems by improving spectral efficiency and enabling complex operations such as multi-target tracking and relative attitude estimation in UAVs. Despite the challenges of power consumption and receiver saturation, Massive MIMO's integration into UAV systems showcases its potential to support advanced navigation tasks that demand high accuracy and robustness.

Edge computing, a core feature of modern 5G networks, plays a crucial role in reducing latency and improving the efficiency of navigation systems. By enabling real-time data processing closer to the source, edge computing supports applications such as vision-based UAV navigation and emergency evacuation systems in large public buildings. The ability to perform computation offloading enhances the overall system responsiveness, making edge computing indispensable in scenarios where quick decision-making is critical.

Although 5G's high-frequency millimeter-wave signals offer greater bandwidth and speed, they are easily obstructed by buildings, trees, walls, and other obstacles{Siddiqui, 2021 #22;Siddiqui, 2021 #22}. This can lead to unstable navigation signals in urban or indoor environments, impacting the accuracy and continuity of navigation. In the future, more technological infrastructure will be developed to support the integration of "5G+BDS

(BeiDou Navigation Satellite System)/GNSS(Global Navigation Satellite System)" for achieving higher precision and stability in global Positioning, Navigation and Timing (PNT).

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All the authors contributed equally, and their names were listed in alphabetical order.

References

[1] Busari SA, Huq KMS, Mumtaz S, Dai L, Rodriguez J. Millimeter-Wave Massive MIMO Communication for Future Wireless Systems: A Survey. IEEE Communications Surveys & Tutorials, 2018, 20(2): 836–869.

[2] Hayat S, Jung R, Hellwagner H, Bettstetter C, Emini D, Schnieders D. Edge Computing in 5G for Drone Navigation: What to Offload? IEEE Robotics and Automation Letters, 2021 Apr, 6(2): 2571–2578.

[3] Siddiqui MUA, Qamar F, Ahmed F, Nguyen QN, Hassan R. Interference Management in 5G and Beyond Network: Requirements, Challenges and Future Directions. IEEE Access, 2021 Apr 15, 9: 68932–68965.

[4] Xing Y, Kanhere O, Ju S, Rappaport TS. Indoor Wireless Channel Properties at Millimeter Wave and Sub-Terahertz Frequencies. In: 2019 IEEE Global Communications Conference (GLOBECOM), 2019.

[5] Bai Y. IMU/ 5G Millimeter Wave Integrated Positioning Method for Driverless Cars [Internet]. [Beijing Jiaotong University]; 2021 [cited 2024 Aug 14]. Available from: https://kns.cnki.net/kcms2/article/abstract?v=sxrP1m9hSI8XbnQfSlz6yIaT4JEfUG6r3A1PASIwi_nHC2vhVXi8QLiEmUmXfVX7qZdJtPyNyJLUIA0NIck55RB5zhFOb7wEV-uF__eOI2ifu3JWlqtn7XNZ179NHi5u3TXr7SscDhQ1LKMgWa0d3aQhPL9UlOLAbQLwT0wCVZOUWMYkcrHFeL8ERPhMYjBr&uniplatform=NZKPT&language=CHS

[6] Wang X, Zhang Z, Zhao N, Zhang Y, Huang D. Indoor Localization and Trajectory Tracking System based on Millimeter-Wave Radar Sensor. In: 2021 IEEE 10th Data Driven Control and Learning Systems Conference (DDCLS), 2021.

[7] Sohrabi F, Chen Z, Yu W. Deep Active Learning Approach to Adaptive Beamforming for mmWave Initial Alignment. IEEE Journal on Selected Areas in Communications, 2021 Aug 1, 39(8): 2347–2360.

[8] Wang T, Li P, Wang R, Sheng Z, Huang L. A Software-Synchronization Based, Flexible, Low-Cost FMCW Radar. IEEE Access, 2020, 8: 115582–115592.

[9] Liu Z, Bhandari A, Clerckx B. λ–MIMO: Massive MIMO via Modulo Sampling. IEEE Transactions on Communications, 2023 Nov 1, 71(11): 6301–6315.

[10] Yang J, Wang B, Chang Z, Zhao Y, Feng Z, Hu F. Joint Trajectory Planning and Transmit Resource Optimization for Multi-Target Tracking in Multi-UAV-Enabled MIMO Radar System. IEEE Transactions on Intelligent Transportation Systems, 2024 Jan 1, 1–17.

[11] Wallace JW, Mahmood A, Jensen MA, Mehmood R. Cooperative Relative UAV Attitude Estimation Using DoA and RF Polarization. IEEE Transactions on Aerospace and Electronic Systems, 2020 Aug 1, 56(4): 2689–2700.

[12] McEnroe P, Wang S, Liyanage M. A Survey on the Convergence of Edge Computing and AI for UAVs: Opportunities and Challenges. IEEE Internet of Things Journal, 2022 Sep 1, 9(17): 15435–15459.

[13] Bi H, Shang WL, Chen Y. Cooperative and Energy-Efficient Strategies in Emergency Navigation Using Edge Computing. IEEE Access, 2020, 8: 54441–54455.