Research on the Application of Integrated Communication and Positioning Technology in Millimeter Wave Systems

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Abstract: To achieve high-precision positioning and efficient data transmission in millimeter wave communication systems, this paper proposes an optimization algorithm based on integrated communication positioning technology. Firstly, establish a signal processing model based on the propagation characteristics of millimeter waves to obtain accurate position information and high-quality data communication capabilities; Secondly, in order to eliminate the impact of multipath interference on positioning accuracy, an adaptive weighted fusion strategy is proposed; Again, based on the physical layer characteristics of millimeter wave systems, a joint optimization model was constructed that comprehensively considers channel state information and user mobility, providing a more accurate description of system performance. Through simulation and field testing, an experimental platform based on the proposed algorithm was built and tested for effectiveness.

1. Introduction

The excellent spectrum resources, high data transmission rates, and fast signal response of millimeter wave communication make it suitable for a wide range of wireless applications, such as wireless broadband access, vehicle-to-vehicle communication, indoor positioning, and many others. It is often necessary to provide precise location information to millimeter wave systems in practical applications. Service performance can be decreased if the positioning accuracy is insufficient. A communication system's reliability is also affected by the quality of the channel, and the environment can also influence multipath effects. As a result, integrating communication and positioning can improve communication system performance and achieve high-precision positioning [1].

In traditional positioning algorithms, position estimation is mostly based on geometric models, which can be divided into two types: time of arrival (TOA) and angle of arrival (AOA). Understanding the propagation environment is crucial to these traditional algorithms. Even though geometric models are widely used in localization, their descriptions of complex propagation environments are not accurate enough, which leads to poor accuracy and robustness in traditional localization algorithms [2]. As a result, it is necessary to conduct in-depth research into the physical layers of millimeter wave systems and to establish more accurate channel models.

To address the problems of inaccurate positioning, large positioning errors caused by multipath effects, and low positioning accuracy in current millimeter wave communication systems, this paper proposes an optimization algorithm based on communication positioning integration technology [3]. Firstly, the millimeter wave propagation characteristic model is reconstructed, and based on this model, advanced signal processing techniques are used to obtain accurate location information of user terminals; Secondly, the multipath interference is corrected to obtain a pure signal, and an adaptive weighted fusion strategy is proposed to accurately locate the target position using the corrected signal; Once again, taking into account the impact of channel state information and user mobility on positioning, and combining experimental phenomena for more accurate modeling, a joint optimization algorithm is used to construct an integrated model of positioning and communication; Finally, the proposed algorithm was validated through simulation and experiments, demonstrating the

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effectiveness of the proposed scheme in this paper [4].

2. Basic principles of millimeter wave Communication Positioning Integration Technology

2.1. Characteristics and Applications of Millimeter Wave Technology

Millimeter wave technology is a concept developed in parallel with modern wireless communication. A high-performance orientation is highlighted in future wireless communication, highlighting the concept of high spectral efficiency, and reflecting the rapid development of mobile Internet and Internet of Things, which has led to increased data transmission rates and more accurate positioning services [5]. However, it is still difficult to achieve a completely consistent understanding when we attempt to construct the definition and essence of millimeter wave technology using standards from certain traditional radio frequency bands. Due to their extremely high frequency range between 30 and 300 GHz, millimeter waves provide unparalleled bandwidth resources for high-speed data transmission, and they also possess unique characteristics such as narrow beams and high directionality, which make millimeter waves ideal for indoor positioning with greater precision and for wireless communication with high speed over short distances. Other applications of millimeter wave technology include radar systems, security checks, and more. It improves system performance while also facing challenges like high propagation losses and weak penetration.

2.2. Overview of Integrated Communication and Positioning Technology

An integrated communication and positioning technology is an important standard in modern wireless communication systems, which encompasses both data transmission and location perception capabilities. The technology is discussed from the perspective of resource optimization and efficiency improvement. It has been speculated that the integration of communication and positioning is the future trend of wireless network development due to the degree of intelligence possessed by wireless networks or the degree of network intelligence [6]. Due to the fact that integrating communication and positioning is more practical to some extent as well as related to information science, it can improve user experience. Integrated communication and positioning have their roots in early radio navigation systems, which use radio signals to determine ship and aircraft locations. Integration of communication and positioning technology is closely related to the rise of the Internet of Things and intelligent transportation technologies. In the field of wireless communication, it has become increasingly important to integrate communication and positioning functions. With the development of 5G technology and post-5G technology, relevant theories have proposed a series of efficient algorithms to simultaneously enhance data transmission rate and positioning accuracy. It was originally based on technical metrics based on signal processing standards, but it has now developed into a research direction covering interdisciplinary integration [7].

3. Decomposition of Integrated Communication and Positioning Methods in Millimeter Wave Systems

3.1. Construction of objective function for integrated positioning and communication

In millimeter wave systems, a method called joint optimization algorithm can be used to achieve the integration of communication and positioning. This algorithm belongs to the multi-objective optimization algorithm type, aiming to simultaneously improve communication quality and positioning accuracy. In joint optimization algorithms, the solution set contains multiple candidate solutions, and the optimal solution to the problem is found through multiple iterative processes. The following will introduce the process of generating candidate solutions and the flow of joint optimization algorithms.

Each candidate solution has a positional sequence attribute and a selection probability attribute. The position sequence attribute of the candidate solution represents a feasible solution, including the activity sequence and the user device sequence executing the activity; The selection probability attribute of candidate solutions represents the selection probability used in the process of constructing feasible solutions, including the selection probability of activities and the user device selection probability corresponding to each activity.

Assuming the number of activities is N and the number of user devices is M, the number of user device sequences that can be allocated to the activities is K. The i-th candidate solution is denoted as S_i, and the position sequence attribute P_i of S_i is represented as

$$P_i = (p_{i,1}, p_{i,2}, ..., p_{i,N}) \quad (1)$$

Among them, $p_{i,j}$ represents a sequence sorted according to the start time of the activity, j represents the jth activity that starts execution, $p_{i,j}$ represents the sequence of user devices that execute the corresponding activity, U is the set of user devices, and represents the sequence of user devices corresponding to the j-th activity that starts execution. Taking the activity allocation scheme in P_i as an example, $p_{i,1}$ represents that the first activity to be executed is a1, and $p_{i,1}$ represents that the user device sequence consisting of user devices u_1 and u_2 executes activity a_1.

Selection probability attribute representation of candidate solution S_i

$$Q_i = (q_{i,1}, q_{i,2}, ..., q_{i,N}) \quad (2)$$

Among them, $q_{i,j}$ is an $(N+1)\times N$ selection matrix, representing the probability of activity selection; $q_{i,j}(k)$ represents the probability of selecting activity a_k as the next execution activity after activity a_j is completed. When $k=0$, $q_{i,j}(0)$ represents the probability of selecting activity a_j as the first execution activity; $r_{i,j}$ is a $N\times M$ selection matrix that represents the probability of selecting user devices to perform activities; $r_{i,j}(m)$ represents the probability of selecting user device u_m to perform activity a_j. The historical optimal position sequence attribute found for each candidate solution S_i is denoted as P_i^*.

In this context, N, M, and K respectively represent the number of different operations involved in the activity, the number of user devices participating in the system, and the number of sequences that can be assigned to user devices for each activity. And $p_{i,j}$ and $q_{i,j}$ are used to describe the specific structure of the solution and its probability of being selected, which are crucial for the algorithm to find the optimal configuration. The framework for constructing the objective function of integrated positioning and communication is shown in Figure 1.

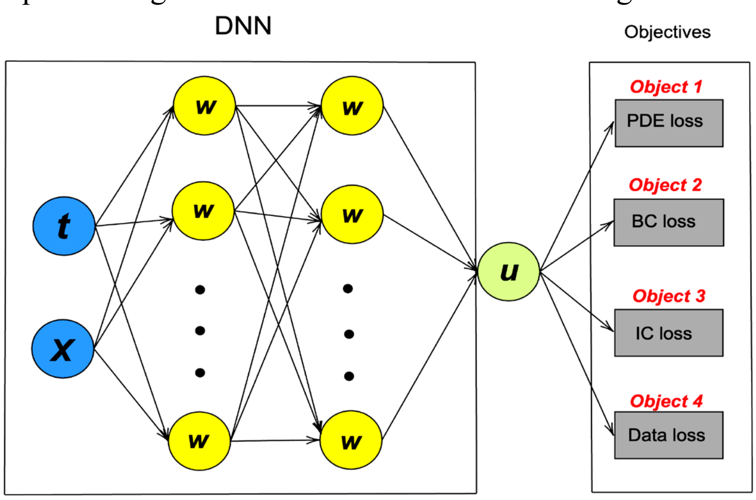

Figure 1: Objective function construction for integrated positioning and communication

3.2. Parameter optimization process based on optimization algorithm

The overall process of the joint optimization algorithm is shown in Figure 1. Firstly, initialize the solution set, and then search for the optimal solution to the problem through multiple iterations. All candidate solutions searched by the joint optimization algorithm are stored in the solution set.

During each iteration, the joint optimization algorithm first updates all candidate solutions. For each candidate solution, first evaluate the fitness value of the position sequence attribute P_i of the candidate solution S_i and normalize all target values according to equation (1). Then, select the target with the best performance of the candidate solution S_i as its main target according to equation (2):

$$z_{i,k} = \frac{f_{i,k} - f^{\min_k}}{f^{\max_k} - f^{\min_k}} \quad (3)$$

$$g_i = \arg\max_k z_{i,k} \quad (4)$$

Among them, $f_{i,k}$ is the k-th target value of the candidate solution S_i in the position sequence attribute P_i ($k \in [1, K]$, K is the number of targets), $f^{\min_k}$ and $f^{\max_k}$ are the minimum and maximum target values on the k-th target in the solution set, and g_i is the index of the main target of the candidate solution S_i.

Next, according to the main objective g_i sort all candidate solutions in the solution set, select N_b candidate solutions that are better than the candidate solution Si as the candidate solution set, and then randomly select a candidate solution from the candidate solution set as the learning example L_i. The candidate solution S_i updates its position sequence attribute P_i^* based on the historical optimal position sequence attribute P_i and the learning example L_i:

$$P_i(t+1) = P_i(t) + F \cdot (P_i^* - P_i(t)) + F' \cdot (L_i - P_i(t)) \quad (5)$$

Among them, F is the scaling factor, F 'is another scaling factor, and t represents the current iteration count. The positional difference between P_i^*, L_i, and P_i is achieved through vector operations. Taking the position sequence attribute as an example, when calculating the above equation, the historical optimal position sequence attribute P_i^*, the position difference between the learning sample L_i and the current position sequence attribute P_i are first converted into vector form. Then, $(P_i^* - P_i)$ and $(L_i - P_i)$ are obtained through vector operation, and the elements less than 0 in the two are set to 0. Finally, the position sequence attribute P_i is updated through vector addition. Similarly, updating the probability attribute Q_i is also achieved through corresponding vector operations.

Afterwards, the candidate solution S_i updates its position sequence attribute P_i based on the updated selection probability attribute Q_i and constructs a new feasible candidate solution through multiple steps. In each step of constructing feasible candidate solutions, the probability attribute Q_i is first selected based on the task selection probability to select a feasible task that satisfies the priority constraint. Then, the probability attribute Q_i is selected based on the user device selection probability to gradually select user devices for the task until the user device sequence meets the task's capabilities and resource requirements. Repeat the above steps until all tasks have been assigned to the user device sequence. Afterwards, evaluate the new position sequence attribute P_i of the candidate solution and update the historical optimal position sequence attribute P_i^* and the solution set. After all candidate solutions are updated, use local search methods to further improve the quality of candidate solutions. When the maximum number of iterations reaches the specified limit, the joint optimization algorithm is terminated and the output solution set is the candidate solution set found by the joint optimization algorithm. The parameter optimization process based on optimization algorithm is shown in Figure 2.

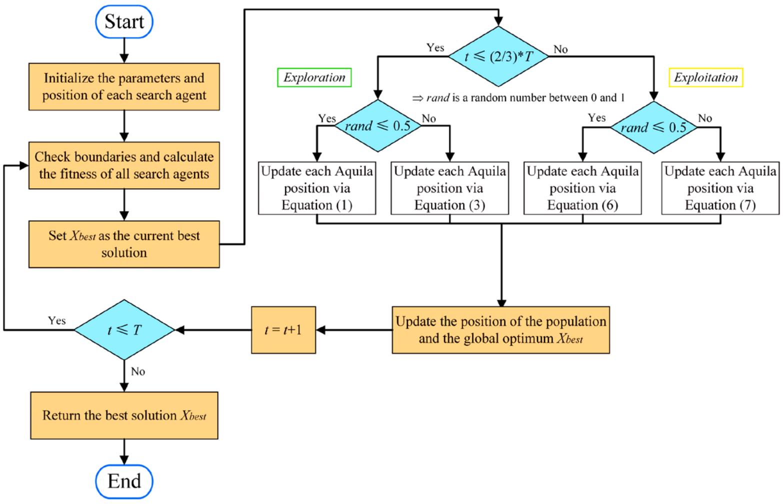

Figure 2: Parameter optimization process based on optimization algorithm

In this context, $f_{i,k}$ represents the performance of each solution for different objectives; $f^{\min_k}$ and $f^{\max_k}$ correspond to the minimum and maximum values of each target in the entire solution set, respectively; $z_{i,k}$ is the normalized target value used to compare the importance of different targets; g_i specifies which objective needs to be optimized the most for a specific solution; F and F 'are used as scaling factors to control the learning rate and balance between new and old solutions; $P_i(t+1)$ represents the position sequence attribute of the selected solution S_i in the next iteration.

4. Analysis of Millimeter Wave Communication Positioning Signal

4.1. Signal implantation and processing methods

High-precision positioning cannot be achieved without the key technology of "signal implantation and processing methods." As a standard and effective tool for improving positioning accuracy and stability, signal implantation and processing are essential components of the millimeter wave communication positioning mechanism. In addition, signal implantation and processing is not only a technical concept, but also an applied concept. As a result, millimeter wave communication positioning algorithms are based on "signal implantation and processing." In general, signal implantation and processing are gradually deduced through engineering implementation, although this path includes attempts at diverse technical solutions, based on theoretical research. All aspects of signal implantation and processing are aimed at improving system performance, from signal design to data analysis. For practical applications, millimeter wave communications positioning should strive to solve interference problems in complex environments. The pursuit of higher resolution brings, however, the dilemma of excessive computing resources consumption. It is important for researchers to continue to improve millimeter wave communication signal analysis's anti-interference ability and processing algorithms. A diagram of the signal implantation and processing methods is shown in Figure 3.

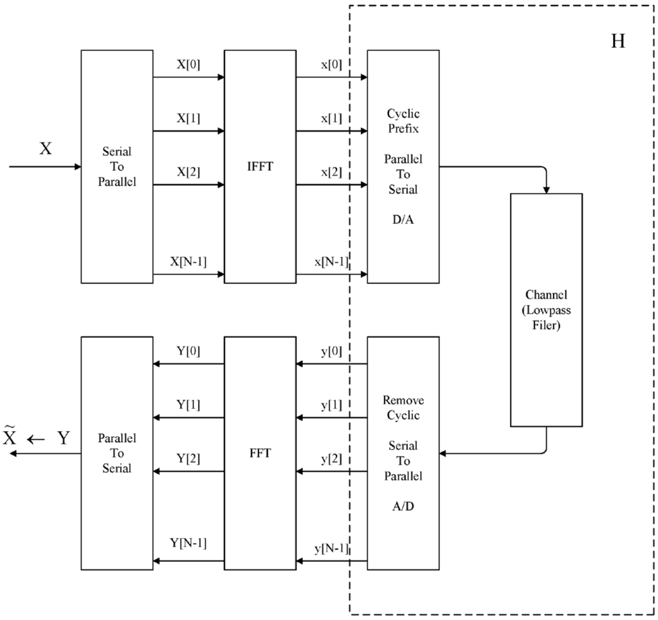

Figure 3: Signal implantation and processing method

4.2. Signal acceleration and synchronization technology

Signal transmission delay has long constrained millimeter wave communication positioning systems' ability to respond in real time. Signal acceleration and synchronization technology has reshaped system performance through optimized algorithms since the 21st century by integrating high-speed data processing with low latency transmission. However, traditional hardware limitations still restrict further improvements. It is still necessary to improve signal acceleration and synchronization technology not only due to uneven allocation of computing resources, but also because of environmental interference [8]. An improved user experience can be achieved by signal acceleration and synchronization, both of which are considered direct ways to achieve high-precision positioning. Nevertheless, software defined radio's practical application role in practical application scenarios needs to be further explored. Likewise, the whole network lacks consistency due to difficulty synchronizing time between different devices. Consequently, it appears that the expected real-time and accuracy goals cannot be met even with advanced acceleration and synchronization technologies [9]. The challenges of signal acceleration and synchronization go beyond technical challenges, and cross-platform compatibility is also an issue.

4.3. Performance comparison analysis

Millimeter wave communication positioning requires high-precision positioning in real-time and with high accuracy, which traditional technologies cannot provide [10]. Most users rate their satisfaction with location services, but there are currently no mechanisms for accelerating and synchronizing signals that are relevant to them. There may be something fundamentally wrong with the technical implementation of this problem. The improvement of positioning performance is often attributed to signal acceleration and synchronization in millimeter wave communications, and their impact on user experience directly reflects the quality of the service [11]. The existing literature, however, is mainly about theoretical analysis and technical solutions, and practical application cases are relatively rare. Testing in real environments is usually difficult. In practical application scenarios, asymmetric information and imperfect models present significant obstacles to technological optimization and user experience enhancement. A comparison of millimeter wave communication positioning performance can be seen in Figure 4.

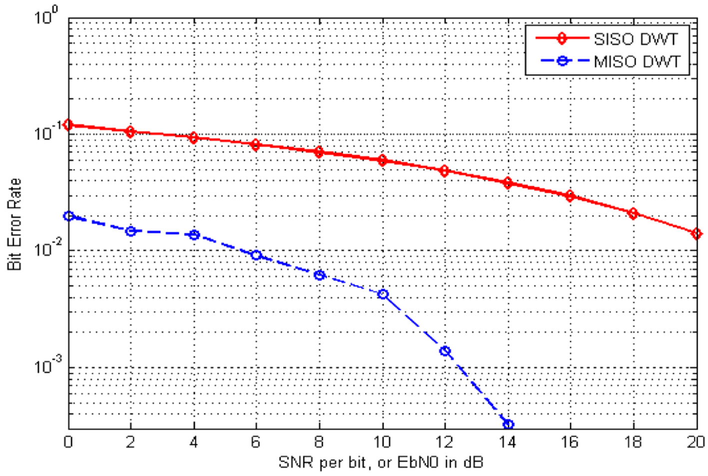

Figure 4: Comparative analysis of millimeter wave communication positioning performance

5. Conclusion

Positioning services using millimeter wave communication technology have made significant progress, posing new challenges and requirements. Synchronization and acceleration of signals are not only symbols of improving "real-time performance", but also crucial to data processing efficiency and maintaining system stability. Modern communication systems are intrinsically designed to be reliable and low latency. A complete framework has been developed for signal acceleration and synchronization based on technological innovation. By optimizing algorithms, modern information technologies, such as software defined radio, have driven the development of positioning systems, enhancing their accuracy and scientificity. A quick response is inherent in a society that is intelligent. Consequently, based on signal acceleration and synchronization, it also addresses the bottleneck of traditional positioning. Overall, millimeter wave communication positioning technology can be developed and improved in a sustainable manner so that it meets the needs of diverse application scenarios, promotes technological advancement in related industries, and improves the level of social informationization.

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