Application of Fresnel Zone Model in Wireless Sensing Field

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Abstract. As a common model in the field of wireless sensing, the Fresnel zone model performs better than traditional deep learning in generalization ability, computational efficiency, robustness, and so on. It shows significant advantages in breath monitoring, gesture recognition, indoor behavior recognition, and so on. In this paper, the typical applications of the Fresnel band model in fine and coarse-grained wireless sensing tasks in recent ten years are listed. With the progress of the research, the concentric circle model, dynamic Fresnel region model, and through-wall wireless sensing model are developed in combination with other methods, which can well solve the wireless perception problem in non-line-of-sight scenes. Or combined with deep learning to develop new ways to solve specific problems. Over the course of development, the emergence of new methods makes the wireless perception scene more complex, Respiratory monitoring can be changed from one-person monitoring to multi-person detection, and the accuracy of gesture recognition and indoor behavior recognition is getting higher and higher.

Keywords: Wireless sensing, Fresnel zone model, concentric circle model, dynamic Fresnel zone model, through-wall wireless sensing model.

1. Introduction

As a new technology means, wireless sensing technology has shown great potential and application prospects in many fields in recent years. Wireless sensing technology mainly relies on the channel status information (CSI) of wireless signals. It senses objects and behaviors in the environment by analyzing changes in signals. The common research methods of wireless perception mainly include pattern- and model-based research methods. Although pattern-based research methods perform well in some applications, their dependence on data and limitations in new environments limit their wide application. In contrast, model-based research methods have obvious advantages in many wireless sensing tasks due to their strong generalization ability, robustness to noise, interpretability, and high computational efficiency.

In the development of wireless sensing technology, Fresnel Zone Model is widely used. By defining multiple Fresnel regions in the radio wave propagation path, the model helps researchers understand the interference and diffraction phenomena in the signal propagation process, so as to predict and interpret the changes in wireless signals more accurately.

At present, the Fresnel zone model is widely used in wireless sensing field. The precision of fine-grained human behavior research, such as breath detection and gesture recognition, is higher than that of traditional machine recognition. At the same time, the Fresnel zone model also shows a good advantage in coarse-grained indoor human behavior recognition.

However, with the complexity and diversification of application scenarios, Fresnel zone model still faces many challenges in practical application, such as the multipath effect, non-line-of-sight propagation (NLOS) and other problems that need to be further studied and solved. For this reason, this paper aims to summarize the typical applications of the Fresnel zone model in the field of wireless perception in recent years and stimulate researchers to combine the Fresnel zone model with other modes or models, develop new models and new methods, and improve the accuracy and range of wireless perception.

2. Fresnel Zone Model Overview

The Fresnel zone originated in the field of optics. Nowadays, in the field of radio frequency, the Fresnel zone concept is a series of concentric ellipsoids with the same focal point, as shown in Fig 1, where the receiving device RX and the transmitting device TX are placed. The NTH Fresnel region boundary is defined as an ellipsoid between the NTH and n + 1 Fresnel regions.

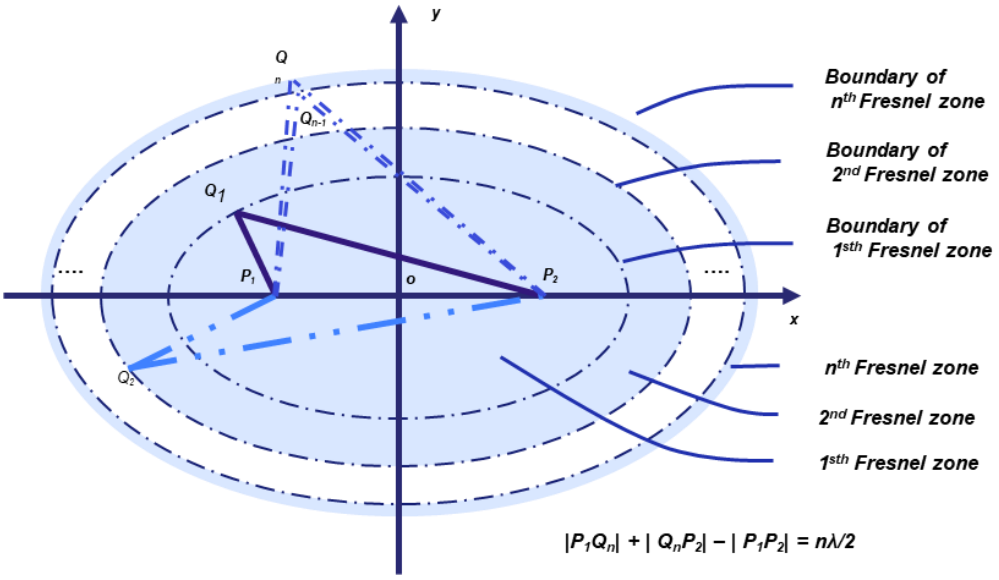


Fig. 1 Fresnel zone geometry

The elliptic equation for each Fresnel region satisfies the constraint relation:

$$|P_1Q_n| + |P_2Q_n| - |P_1P_2| = n\frac{\lambda}{2} \quad (1)$$

Where Qn is the point on the NTH Fresnel region and λ is the given radio wavelength. From the boundary relation, we can get that when the object is at the boundary of the Chifresnel region, the signal phase is synchronized and the signal is added. When the propagation path passes the boundary of the even Fresnel zone, the signal phase is not synchronized and the signal cancels. As shown in Fig 2.

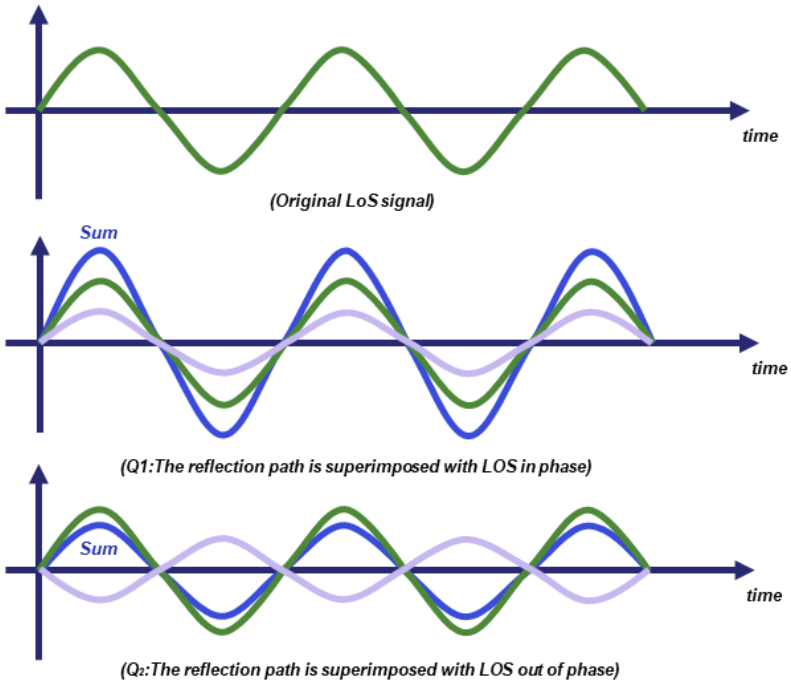


Fig. 2 Signal superposition in odd and even Fresnel area

3. Fresnel Zone Model Application Example

3.1. Respiratory Monitoring

3.1.1. In LoS scenes

In 2016, Zhang Daqing's team introduced the Fresnel zone model into the indoor environment for the first time and used the CSI provided by WIFI devices for respiratory rate monitoring. By modeling the human body in the semi-cylinder shown in Fig 3 to simulate the chest movement during breathing, the chest displacement is converted into a phase change to characterize how human breathing affects the received signals. The study developed theories linking the depth, position, and direction of the breath to the detectability of the breath [1].

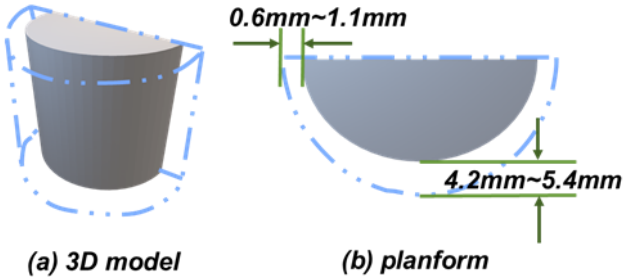
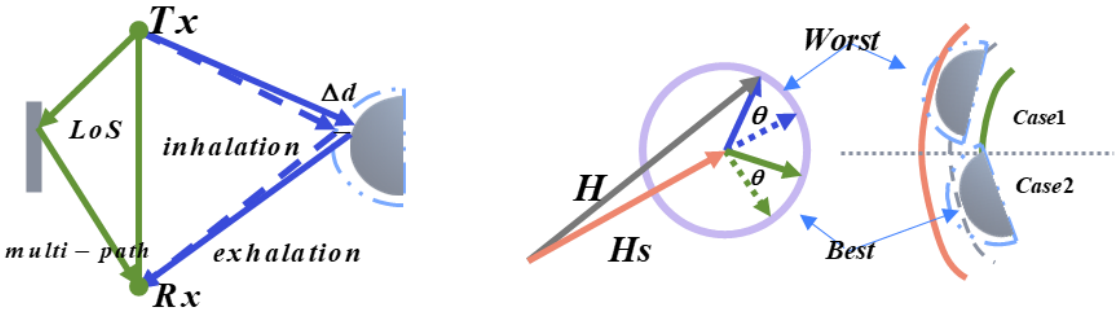
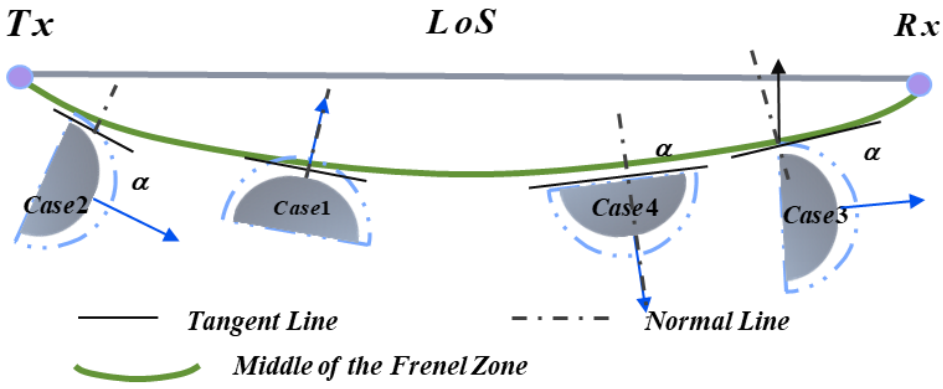


Fig. 3 Semi-cylindrical human respiration model [1]

When the human body was in different positions in the Fresnel zone, Zhang et al. discovered that in each Fresnel zone, the least favorable position for centimeter-level body detection was near the boundary, while the most favorable position was in the center of the zone, as illustrated in Fig. 4(a). Moreover, the displacement of the chest during breathing differs between the front and central areas, so the phase change of the received signal is affected not only by the depth of breathing and the position of the body, but also by the direction of the body. When the body faces 0 degrees (facing the WiFi device), the signal change is the most obvious, and the detection effect is the best, as shown in Fig 4 (b).



(a) The bodies are in different locations in Fresnel



(b) The human body is in different directions in Fresnel

Fig. 4 Influence of exploration location and direction on detection results [1]

When a single user operates with a WiFi transmitter and receiver pair, the visual distance must not exceed 3m, otherwise, effective detection of CSI signals cannot be guaranteed even under the optimal user location and body orientation. Using a pair of WiFi Tx/Rx for two users, it is necessary to ensure that each user's location is in the center of the zone in order to effectively separate and detect respiratory signals, and it is necessary to assume that the respiratory patterns of different users are different and relatively stable. It is difficult to distinguish individual respiratory signals, and it is even more difficult to detect multiple people at the same time.

In 2021, Zhang et al. proposed a CSI quotient model using MIMO technology [2], which closes the gap between the ideal CSI in the Fresnel zone model and the actual CSI obtained from standard WiFi devices, expands the perception range, eliminates the perception blind area caused by the unavailability of phase information, and realizes the wall-through sensing capability. However, there are still challenges in dealing with complex human movements, such as gesture recognition, especially when multiple body parts are involved.

For the simultaneous detection of multiple people, Yin et al proposed an innovative system named MoBreath for the first time in 2021 [3], which used the Wi-Fi CSI extracted from smartphones to monitor respiratory rate. To improve the accuracy of respiratory monitoring, this paper proposes an algorithm to select the optimal sub-carrier among many noisy CSI sub-carriers, and proposes a smart phone placement strategy that combines the Fresnel zone model. The results showed that, MoBreath could achieve accurate breath-sensing performance with two random smartphone placements. For different body positions, such as sitting and lying down, the accuracy of the breath sensing can reach 96% and 94%, respectively. With a 20cm wall, the accuracy rate can also reach 91.2%. Meanwhile, MoBreath is capable of delivering highly accurate results even in complex situations, such as when the target is covered by a blanket or when there are multiple targets within the sensing range. However, due to the difficulty of removing severe noise during movement (such as walking or running), the system cannot accurately monitor breathing when the target is moving.

By further considering the multifrequency diversity of subcarriers, Zhang et al. constructed a breath detection diagram [4] to indicate where different subcarriers can detect breath. As shown in Fig 5, in numerous areas within the inner Fresnel band, human chest movements go undetected by any subcarrier because of the existence of blind spot.

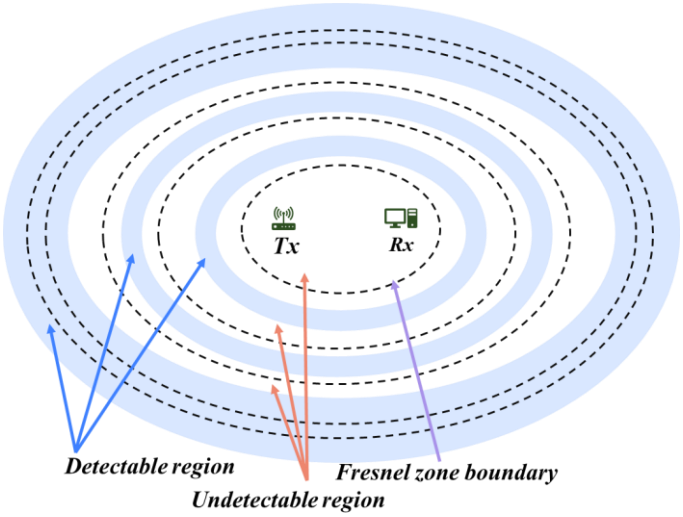


Fig. 5 A map illustrating respiration detection within the Fresnel zone using multiple subcarriers. [4]

Based on this, Xie et al. improved the Fresnel zone model in 2022. By putting the transmitter and receiver together, the Fresnel ellipses with different adjacent distances became concentric circles with equal adjacent distances, as shown in Fig 6. The results show that the model has a high velocity measurement accuracy, and the measurement error is less than 0.4cm/s. The respiratory monitoring system can monitor human respiration more accurately within a range of 6 meters, with an error of less than 0.7 times/min.

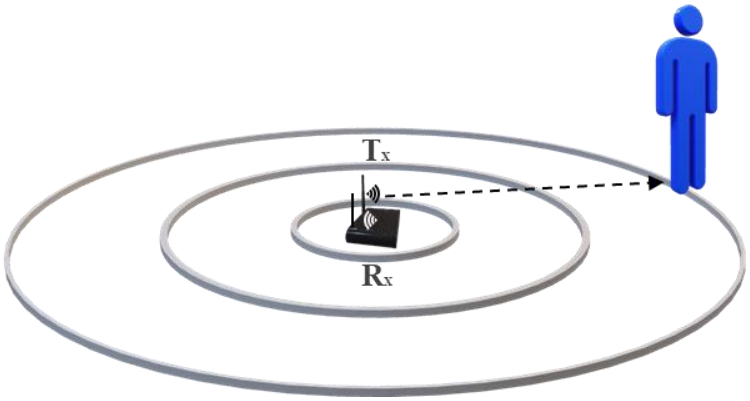


Fig. 6 Concentric circle model [5]

3.1.2. In NLoS scenes

Most of the above models are applicable to LOS scenarios where wireless signals are sent directly to the target, and the reflected signals are subsequently received by the receiver. However, the actual monitoring environment is often NLOS scenes that are blocked by walls or furniture. In 2023, Zhang et al. systematically established Fresnel model of refraction perception [6], and the original Fresnel model serves as a special case of this model when no occlusion is present. In the through-wall scenario, the signal variation as the object moves through the Fresnel zone is depicted in Fig. 7.

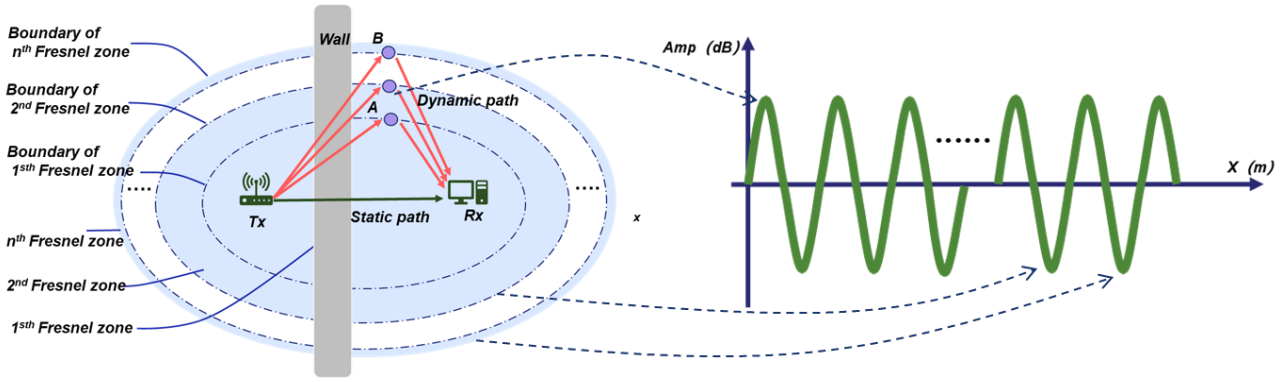


Fig. 7 The signal changes as the object passes through the Fresnel zone in the through-wall scenario [6]

In scenarios involving walls, Wi-Fi signals display two primary characteristics: When a vertical barrier exists between Wi-Fi transmitters and receivers, the Fresnel zone becomes "compressed" compared to an open-space scenario. In such through-wall cases, the Fresnel zones take the shape of flatter elliptical rings instead of the usual ones. This situation results in more frequent fluctuations in the received signal amplitude, enhancing spatial resolution. As a result, even smaller object movements lead to periodic changes in signal amplitude, aiding in the detection of subtle motions. Furthermore, the wall significantly dampens the energy, causing a notable reduction in the signal amplitude received. The study's extensive tests in typical through-wall environments reported breath detection errors of under 0.5 bpm, with the subject being positioned less than 2 meters away from the transmitter-receiver line.

In 2024, Zhang et al. further studied the mechanism of through-wall sensing, proposed a new index of compression ratio (CPR) to evaluate the ability of WiFi signals to sense through walls in different scenarios, and designed a collection of algorithms to assist in deploying the sensing system [7]. In addition, on the basis of the previous research, the type and number of walls, as well as non-vertical cases were added to the study. The experimental results showed that the perceptual performance was significantly different when the participants were located in different regions, and the perceptual performance of the compressed region was better than that of the extended region. This experiment comprehensively and quantitatively characterizes the sensing mechanism and capability of wireless signals in a wall-penetrating scene.

3.2. Gesture Recognition

Fresnel zone model focuses on the sensitivity to weak signals and the ability to accurately detect periodic movements in respiratory monitoring. Similarly, as a fine-grained movement, Fresnel zone model is mainly used to improve spatial resolution and distinguish complex gestures in gesture recognition.

In 2019, Ren et al. proposed an intelligent and robust non-contact gesture recognition iGest system based on Fresnel zone model [8]. The system uses WiFi physical layer information for gesture recognition, is independent of signal amplitude and is independent of the user's location. The findings indicate that the average accuracy of recognizing basic gestures reaches as high as 91%. Meanwhile, the average accuracy for identifying complex gestures exceeds 85%, and it is location-independent and robust.

In 2023, Qin et al. achieved high gesture recognition accuracy in all directions through the circular antenna arrangement strategy [9]. First of all, the effect of the user's change of direction is mitigated by the arrangement of circular antennas. Then, the Fresnel region model is used to estimate the orientation of the user. Ultimately, a feature mapping model for users across varying directions is developed, aligning the gesture features in the predicted direction with those in the baseline direction, thereby mitigating the impact of directional changes. The study had an average recognition accuracy of 92.38 percent for five common gestures.

3.3. Coarse-grained Behavior Recognition

3.3.1. Indoor behavior recognition

Static behaviors indoors are among the simplest forms of activity. In prior research, Fei and colleagues utilized the Fresnel zone model for static indoor positioning [10], revealing that their method had an average error of 33.6 cm within a 47.6 m² space and 31.2 cm within a 40.7 m² space.

In 2022, Ding and the team analyzed the relationship between CSI and human actions using the Fresnel zone model and developed a multi-modal fusion-based human activity recognition framework in a WiFi environment, utilizing AdaBoost [11], as illustrated in Figure 8. The scheme achieved over 95% accuracy in identifying basic human actions like walking, running, and sitting across two different scenarios.

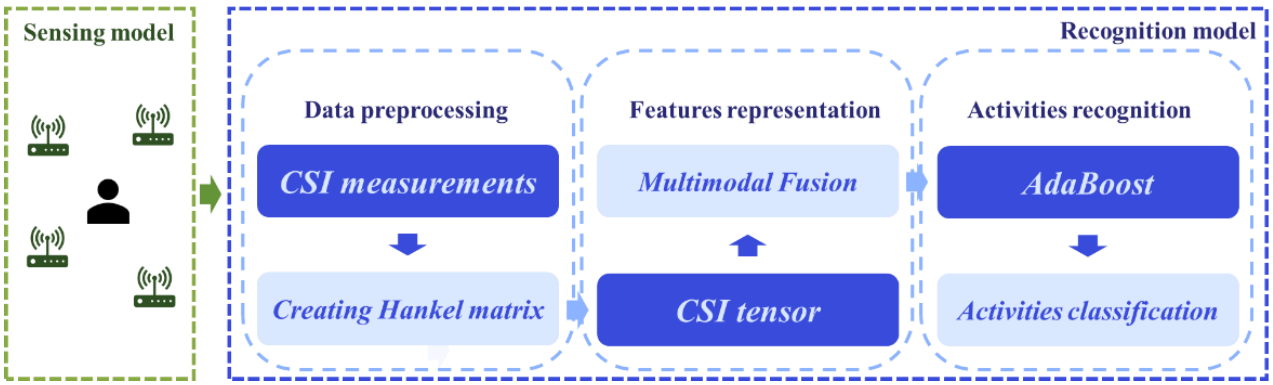


Fig. 8 Scheme architecture based on multi-mode fusion -AdaBoost [11]

In later studies, Liu et al. proposed a dynamic Fresnel zone model [12] and established a theoretical model based on mobile WiFi. On this basis, the classification accuracy of the five activities on the receiver side reaches 98%. Xu et al proposed a hyperbolic tracking model to achieve accurate sensing in the case of NLOS, which reduces the tracking error of 0.36m compared with the Fresnel region model [13].

3.3.2. Applications in emerging industries

In the dynamic ship environment, the traditional positioning method is not good in the dynamic and complex ship environment because the ship's dynamic deformation and metal structure will seriously affect the wireless signal propagation and positioning accuracy. Therefore, in 2024, Liu et

al. first proposed a directional Fresnel signature (DiFS) positioning framework based on Wi-Fi signals [14]. The method takes advantage of the "skin effect" caused by the ship's metal surface to enhance positioning accuracy without relying on fingerprint databases or extensive pre-deployment efforts. The results demonstrate that the DiFS system attains positioning accuracies of 0.9 m in LoS conditions and 1.2 m in NLoS conditions, outperforming other current approaches by a substantial margin.

3.4. Summary of Research Models

The Fresnel zone model has been widely used in wireless sensing field in recent years. In the process of development, Fresnel zone model is mostly combined with other models rather than used alone. In addition, with the optimization of the model method, the range of wireless perception is gradually expanded and the precision is gradually improved, and the perception scene is also transferred from line-of-sight scene to non-line-of-sight scene, and the multipath effect is also being conquered. Typical applications are summarized in Table 1.

Table 1. Summary of research methods based on Fresnel zone model

Application	Year	Reach method	Performance
Respiratory monitoring	2017	Fresnel zone model	The visual distance of a single user is less than 3m, which is difficult to monitor for two users
	2021	Fresnel zone model、CSI-ratio model	Expand the sensing range and eliminate phase blind spots
	2021	Fresnel zone model、Mobreath system	The accuracy of multi-person static monitoring is greater than 90%
	2022	Concentric circle model based on Fresnel zone	Speed measurement error is less than 0.4cm/s, The error within 6m is less than 0.7 times/min
	2023	through-wall wireless sensing model	Error is less than 0.5bpm
	2024	through-wall wireless sensing model	Comprehensively and quantitatively characterize
gesture recognition	2019	Fresnel zone model、iGest system	The recognition rates of basic gestures and complex gestures were higher than 91% and 85%, respectively
	2023	Fresnel zone model、circular antenna arrangement	The recognition rate of 5 gestures was 92.38%
Coarse-grained behavior recognition	2020	Fresnel zone model	The average error within 47.6m2 is 31.2cm The average error within 40.7m2 is 33.6cm
	2022	Fresnel zone model + AdaBoost	Simple behavior recognition accuracy is greater than 95%
	2023	Dynamic Fresnel zone model	The classification accuracy of 5 behaviors is as high as 98%
	2024	hyperbolic tracking model	The tracking error is reduced by 0.36m in the case of NLOS
	2024	DIFS model	LOS and NLOS have positioning accuracy of 0.9m and 1.2m respectively

4. Conclusion

In the field of wireless sensing, the Fresnel zone model, as one of the most widely used research methods, has been developed in recent years and has been combined with other models or modes to put forward many innovative solutions. Through continuous improvement of the model, new models such as the concentric circle model, refractive sensing Fresnel model and dynamic Fresnel model have been developed successively. The emergence of these new models has significantly improved the accuracy of tasks such as breath monitoring, gesture recognition, and behavior recognition. In addition, the application of the Fresnel zone model in emerging fields has shown great practical significance.

Looking to the future, with the further development of technology, Fresnel zone model will play a more important role in the field of wireless perception. This will not only promote the accuracy and efficiency of wireless sensing technology, but also provide strong theoretical and technical support for emerging application scenarios, and further broaden the application prospect of Fresnel zone model.

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