Human Activity Sensing with Wireless

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Wireless networks have been widely deployed with a high demand for wireless data traffic. The ubiquitous availability of wireless signals brings new opportunities for non-intrusive human activity sensing. To enhance a thorough understanding of existing wireless sensing techniques and provide insights for future directions, this survey conducts a review of the existing research on human activity sensing with wireless signals. We review and compare existing research of wireless human activity sensing from seven perspectives, including the types of wireless signals, theoretical models, signal preprocessing techniques, activity segmentation, feature extraction, classification, and application. With the development and deployment of new wireless technology, there will be more sensing opportunities in human activities. Based on the analysis of existing research, the survey points out seven challenges on wireless human activity sensing research: robustness, non-coexistence of sensing and communications, privacy, multiple user activity sensing, limited sensing range, complex deep learning, and lack of standard datasets. Finally, this survey presents four possible future research trends, including new theoretical models, the coexistence of sensing and communications, awareness of sensing on receivers, and constructing open datasets to enable new wireless sensing opportunities on human activities.

Keywords: wireless sensing ; activity recognition ; counting ; detection ; tracking

1. Introduction

The rapid development and the pervasiveness of wireless networks has stimulated a surge in relevant research of wireless sensing, including detection, recognition, estimation, and tracking of human activities. Wireless sensing reuses the wireless communication infrastructure, so it is easy to deploy and has a low cost. Compared to sensor-based and video-based human activity sensing solutions, wireless sensing is not intrusive and of fewer privacy concerns. Specifically, video-based sensing is restricted in line-of-sight (LoS) and light conditions and raises more privacy concerns. Sensor-based sensing incurs extra cost due to additional sensors, as well as accompanying some inconvenience on wearing for users.

During the propagation of the wireless signal from the transmitter to the receiver, the wireless signal is affected by obstacles in the transmission space, resulting in attenuation, refraction, diffraction, reflection, and multipath effects. Therefore, wireless signals arrived at the receiver carry the environmental information. Human activity will affect wireless signal propagation, which can be captured inside the received signals. Since different activities may lead to various patterns inside wireless signals, it can be used for different wireless sensing applications. Recent research has applied wireless sensing on motion detection, activity recognition, action estimation, and tracking. Various wireless sensing applications target their specific purpose and use unique signal processing techniques and recognition/estimation algorithms. To enhance a thorough understanding of existing wireless sensing techniques and provide insights for future directions, this survey conducts a review of the existing research on human activity sensing with wireless signals.

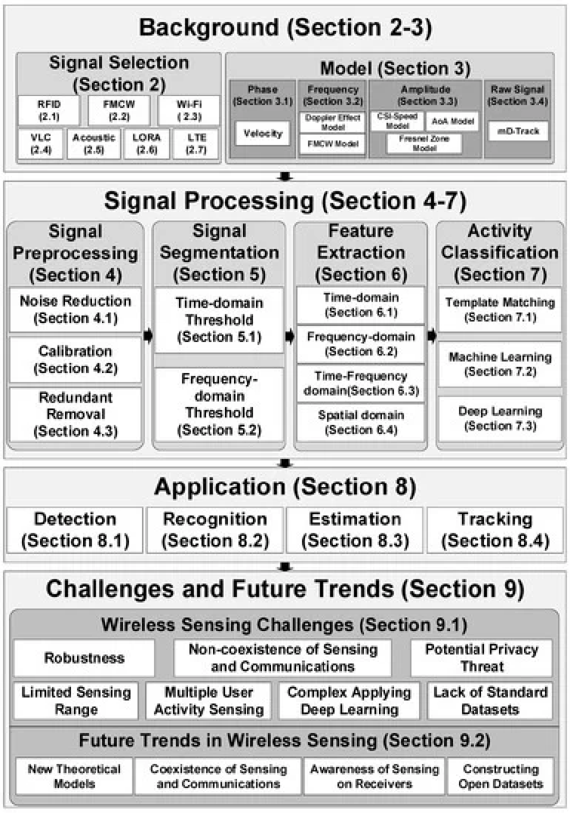

Figure 1. Overview of wireless sensing and survey organization.

Figure 1 shows an overview of the survey. After discussing the related work in Section 2, we introduce the background and characteristics of wireless signals in Section 3. The theoretical models from wireless signals to the features of human motion are discussed in Section 4. The signal preprocessing for noise and outlier reduction are shown in Section 5. The preprocessed signal sequences are fed to the detection module to cut out the signal segment corresponding to every single action, shown in Section 6. The feature extraction applied on the action segment are described in Section 7. The activity classification algorithms are compared in Section 8. According to the output types, different applications of wireless activity sensing are reviewed in Section 9. With the development and deployment of new wireless infrastructure, the challenges and future trends for enabling new sensing applications and capabilities are discussed in Section 10. The main contributions of this survey are as follows.

1. We provide a comprehensive review of human activity sensing with wireless signals from seven perspectives, including wireless signals, theoretical models, signal preprocessing techniques, activity segmentation, feature extraction, classification, and application.
2. We discuss the future trends on human activity sensing with wireless signals, including new theoretical models, the coexistence of sensing and communications, awareness of sensing on receivers, and constructing open datasets.

2. Challenges and Future Trends of Wireless Sensing

This section presents the challenges and future trends for both current and future human activity sensing solutions with wireless signals.

2.1. Wireless Sensing Challenges

From the discussion on the theoretical model and signal processing process, the existing research shares the following common challenges.

Robustness: All the theoretical models are based on the multipath analysis to sift out the motion impact on the received signals. Most research add limitations to the experimental environment to analyze the motion impact through multipath analysis. First, there should not be other persons or moving objects around. Other people or moving object’s actions are also captured by the received signals, which makes it hard to sift the target person’s action effect. Second, the action performer is often needed to be on a fixed position from the sender and receiver of the signal in advance for learning-based methods. Otherwise, the learning model would fail to detect or recognize activities. Third, there are often some specific areas for activity recognition. For the Fresnel Zone model, most research takes place at the boundary on the first 8–12 FFZs in deployment. However, it is ridiculous for users to calculate this specific place in reality. When targeting the real scenarios of wireless motion sensing, all the above limitations should be eliminated. It may require some new theoretical models to construct relations between human motion and wireless signals or some novel signal processing methods.

Non-coexistence of sensing and communications: Wireless infrastructures are designed for signal communications, not for sensing applications. The existing approaches require deploying and controlling both the sender and receiver of the wireless infrastructure. Some sensing applications even require a high frequency of continuous sinusoid signals to achieve high performance. This adds the burden to the scarce bandwidth resources and results in reduced communication performance and efficiency. Moreover, sending the continuous sinusoid signals also affect the communications between nearby wireless devices.

Potential privacy threat: Wireless activity sensing takes advantage of non-intrusive and non-obtrusive. However, it still introduces some privacy concerns. As shown in Section 8, existing researches have been able to sense and estimate some daily activities and fitness activity by indoor wireless infrastructure. Such information can be leaked to malicious attackers when the victim may be unaware of the existence of wireless sensing. This imposes a conflict with the robustness issue, which targets on improve sensing under various scenarios. So new techniques or algorithms are needed to ensure users' right to know and control the wireless sensing systems, especially the receivers beforehand.

Multiple user activity sensing: Wireless signals are sensitive to any movements in the sensing area, because any motions may change the multipath propagation of the wireless signals. When multiple persons are sharing the same physical space, the received signals will contain all the impacts by all the persons' motions. Existing FMCW and antenna array-based solutions like [17] can track the hand gestures of multiple people simultaneously, leveraging a directional antenna array. For other wireless signals, a promising way to isolate concurrent activities of different people is to separate sensing space with a complex web of wireless links in the area. Nevertheless, it is still challenging to address the effect of multiple users and recognize different actions conducted by different users with a limited number of wireless links.

Limited sensing range: Although multiple types of wireless signals can be used in human activity sensing, the sensing range is still limited. For example, acoustic-based sensing has a sensing range of 1–2 m, while RFID and WiFi have a sensing range of 2–8 m. The sensing range of VLC is 3–7 m. While LoRa signals have a communication range of 10 kilometers, the current sensing range is below 100 m. Moreover, the applicable sensing systems are still lacking for outdoor environments due to the limited sensing range.

Complex deep learning: Some CSI-based activity recognition applications exploit deep learning approaches, for they can automatically extract high-level features from CSI streams for classification. The deep learning approaches, however, require not only an extensive training set to train the underlying parameters of the learning network and but also a comparable computation and storage capacity to perform training. Therefore, it adds to the burden on the users to collect training samples and maybe not computable on resources limited devices such as wearable and edge devices.

Lack of standard datasets: Currently, most wireless activity sensing studies evaluate their performance using their dataset. Researchers have to recruit some volunteers to conduct many types of actions to collect wireless signal streams. Moreover, the experimental environments are often chosen according to the particular targets of the applications. Consequently, the system performance often depends on the deployment and the collection process, which makes it difficult for comparison among different studies.

2.2. Feature Trends in Wireless Sensing

This section presents future trends in addressing the above challenges and issues.

New theoretical models: The existing model concentrates on the reflection of the human body to the signal propagation, which is captured through the multipath effect. The signal reflection from the human body to the receiver often requires specific positions and angles. It imposes the limitation on the application environment. For example, if the action is extracted from the received signals through the signal diffraction model, the restriction of the specific position may be eliminated. As long as the human performs activities close to the receiver, it will create the diffraction effect with similar patterns inside the received signals. The diffraction model may solve the robust challenge as the diffraction effect depends little on the objects at a certain distance away. If every user has her/his wireless signal receiver, the diffraction effect will naturally separate the sensing space for each user, which also solves the challenge of multiple users. Moreover, a new theoretical model will guide the activity classification process, which may eliminate or reduce the complexity of applying deep learning.

Coexistence of sensing and communications: The major obstacle for the coexistence of sensing and communication is that current solutions need to control the sender of wireless infrastructure and require specific continuous signals for sensing. If the wireless signals already in space can be directly for sensing, the sensing system may only focus on listening and does not need to control the sender of infrastructure. Then the coexistence of sensing and communications can be realized. Moreover, a wireless sensing solution with only receivers may apply the mobile signal infrastructure, which has the advantage of ubiquitous coverage and tackles the sensing range limit.

Awareness of sensing on receivers: The privacy concerns come from that specific systems may make use of some indicators of the received signals for sensing purposes. The tools to control and report on the usage of received signals except communication are of importance. Moreover, more research efforts should be concentrating on the signal receiver of smartphones. The reason is two-fold. Firstly, smartphones are ubiquitous receivers as people carry them all the time. Secondly, users are familiar with the privacy control procedure with smartphones [141], so the signal usage tool to control privacy can be quickly adopted by the users.

Constructing open datasets: It is still an open question to construct the standard datasets for wireless sensing research. When constructing open datasets, many factors have to be carefully chosen, including test environments, deployment of wireless transceivers, types of wireless signals, number of volunteers, differences among volunteers, action types, and size of samples. An open standard dataset will help accelerate the wireless sensing study and improve performance evaluation and comparison.

According to the directions mentioned above, more research efforts should be put on the wireless sensing solution with just a smartphone as the receiver, which directly makes use of ubiquitous mobile signals for sensing under the guidance of a new theoretical model between human motion and wireless signals.

3. Conclusion

This survey gives a comprehensive review of the background of wireless signals, the theoretical models from wireless signals to human actions, signal pre-processing techniques, signal segmentation techniques, feature extraction, activity recognition, and applications of wireless sensing. The article highlights seven wireless sensing challenges on human activities: robustness, non-coexistence of sensing and communications, potential privacy threat, multiple user activity sensing, limited sensing range, complex deep learning, and lack of standard datasets. Finally, the survey points out four future research trends: new theoretical models, the coexistence of sensing and communications, and awareness of sensing on receivers, and constructing open datasets.