Wireless AI

With this groundbreaking text, discover how wireless AI can be used to determine position at centimeter level, sense motion and vital signs, and identify events and people. Using a highly innovative approach that employs existing wireless equipment and signal processing techniques to turn multipaths into virtual antennas, combined with the physical principle of time reversal and machine learning, it covers fundamental theory, extensive experimental results, and real practical use cases developed for products and applications. Topics explored include indoor positioning and tracking, wireless sensing and analytics, wireless power transfer and energy efficiency, 5G and next-generation communications, and the connection of large numbers of heterogeneous IoT devices of various bandwidths and capabilities. Demo videos accompanying the book online at www.cambridge.org/WirelessAI enhance understanding of these topics.

Providing a unified framework for wireless AI, this is an excellent text for graduate students, researchers, and professionals working in wireless sensing, positioning, IoT, machine learning, signal processing, and wireless communications.

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‘Wireless AI is changing the world by enabling wireless sensing and tracking to an unprecedented level. This is the first book on major breakthroughs in this emerging field. A must read!’

Sadaoki Furui, *Toyota Technological Institute at Chicago*

‘*Wireless AI* is an exciting and timely book that provides the reader with the background and material needed to not only ride the wave of technological advancement but also contribute to it. Paradigm-shifting advancements, like time-reversal, cloud-RAN, motion detection and localization, and waveform designs are described in detail. *Wireless AI* is an innovative text that is sure to help engineers and students contribute to the rapidly evolving fields of wireless sensing and communications.’

Wade Trappe, *Rutgers University*

‘. . .an excellent book on wireless AI, with unique and comprehensive coverage, for both researchers and practitioners.’

Geoffrey Li, *Georgia Institute of Technology*

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Wireless Sensing, Positioning, IoT, and Communications

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To the Origin Wireless team for the exciting journey of scientific discovery and the dream of making the world a better place.

Contents

Preface

We have many senses. We can see with our eyes, but only to the limit of line-of-sight. We can hear with our ears, we can smell, we can taste, and we can touch. These are the five senses that we rely upon in our daily life and living.

As the smart phone and smart Internet of Things (IoT) devices are connected with radio frequency signals, Wi-Fi is ubiquitous everywhere indoors, long-term evolution (LTE) is available in almost every corner of the world, and future 5G systems will be more powerful. We rely on wireless radios for communications, chatting, surfing Internet, seeing each other via Facetime, sending text messages, etc., while we are at home, driving, eating, or on the move. Wireless radios enable us many new modern conveniences to the point that we simply cannot live without them.

But can wireless radios offer us a new sense – a "sense" that can help us track people and devices, monitor our environments, detect our activities, even beyond the limit of our vision, hearing, and touch? Indeed, if there is such a "sense," it can qualify as a new intelligence that has been a fantasy for many for so long. No wonder the whole world has been trying to uncover such a new breakthrough to make this dream possible.

In fact, when one refers to "wireless," it is no longer in the narrow sense of communications. It has been for so long that we have been only concerned with the messages sent to us. We try to remove interference, equalize the channel, decrypt the code, and decode the message. Yet we have ignored (or are simply unaware) that the radio signals come with them containing information about our environment and activities. If we can make sense of the radio signals, as if we are evolving to a new sixth sense that allows us to sense/detect/track/recognize our environments and activities and communicate, it is in essence a new intelligence. The information analytics, signal processing, and machine learning that enable such a new intelligence constitute an emerging field of wireless artificial intelligence (AI).

So what is wireless AI? It is to use wireless/radio waves/signals to make sense of our environments, detect/monitor our activities, track and locate users/objects, connect "things" together and empower them, and offer a platform for future communications.

But how can we accomplish that vision? There have been many approaches in recent years in the research community attempting to unlock the secret. In this book, we would like to offer our view by combining the physical principle of time reversal and signal processing/information science to answer some difficult questions that seemingly no better solutions were obtained over the attempts of the last three decades. We have developed a unifying framework to enable the wireless AI dream as we envision.

When one uses radio signals, multipaths always come with it, especially in indoor environments. It has been a long time that we consider multipaths as interferences, noise, or simply nuisance. Previous attempts have always been trying to take them out or at least to neutralize or compensate for their "bad" effects, but there has been too little or no effect because the profiles of multipaths change from location to location, and how can one tell which multipath is a good one and which is not? Under such a thinking paradigm, the struggle continues, and the problem remains.

With the ever-increasing large bandwidth, more and more multipaths can be seen. Each multipath can be viewed as a virtual antenna/sensor located at the direction where it comes from with a distance equal to the speed of light times the time of arrival. Therefore it is as if there are a tremendous number of virtual antennas surrounding us, appearing at our disposal on demand.

The question is, how do we harvest multipaths? Two approaches are by increasing power and bandwidth. The larger the transmitting power, the more radio waves can bounce back and forth around the environment, therefore the more observable number of multipaths. However, oftentimes such a transmitting power is limited by regulations or standards. The other means is to increase the bandwidth in that the larger the bandwidth, the better the time resolution to reveal more multipaths.

Each of these multipaths is in essence a degree of freedom, ready for any use. But how can we control them to serve our purpose? As they are surrounding us virtually, we have to resort to the physics in that we have to generate a waveform to reach out to "them" and control them to achieve the desired effect. One such physics is the principle of time reversal, where we use the time-reversal waveform to control the multipaths to generate the well-known focusing effect.

We have found that by using enough bandwidth in a typical indoor environment, such a focusing effect can be reliably produced. By using the 5 GHz ISM band, for example, we can produce a focusing ball of about 1–2 cm in diameter. If using the 60 GHz band, then it will goes down to the millimeter level. Such an effect serves as the fundamental basis for us to be able to perform indoor positioning with the unprecedented accuracy of centimeter/millimeter, under both line-of-sight and non-line-of-sight conditions.

In fact, with the use of machine learning and signal processing, a revolutionary AI platform can be built to enable many cutting-edge Internet of Things applications that have been envisioned for a long time, but have never been achieved.

This book, *Wireless AI: Wireless Sensing, Positioning, IoT and Communications*, aims at providing comprehensive coverage of fundamental issues that form an artificial intelligence platform that consists of many radio analytic engines for a wide range of applications, including the world's first-ever centimeter-accuracy indoor positioning/tracking, wellness monitoring, home/office security, radio human biometrics, health care, wireless charging, and 5G communications. A goal of the book is to provide a bridge between advanced scientific research and practical industry design and implementation to offer readers a glimpse of what the future wireless AI can achieve.

We first start from the principle of time reversal and effective bandwidth in Chapter 1 to lay out the fundamental concepts for the rest of the book. In Part I, we address the issues of indoor positioning and tracking. Chapter 2 demonstrates that the use of time reversal at 5 GHz with the entire 125 MHz ISM band can produce a focusing ball of 1–2 cm, which translates to an indoor positioning scheme of the same accuracy. Note that the pinpoint locationing of time-reversal focusing effect regardless of any indoor conditions such as line-of-sight and non-line-of-sight inherently implies that the notion of walls and obstacle no longer exists. It is as if there are no walls nor obstacles in the space. In Chapter 3, we show how to use standard Wi-Fi devices to achieve the same centimeter accuracy by leveraging multiple antennas to achieve a large effective bandwidth, and in Chapter 4, we leverage frequency hopping for a large effective bandwidth to again achieve centimeter accuracy of positioning. Note that if 60 GHz Wi-Fi devices are used, the focusing ball will be at the millimeter range in diameter, and therefore one can expect a millimeter level of accuracy. Then, in Chapter 5, we present our discovery that when the number of multipaths is large enough, the focusing ball's energy distribution follows a Bessel function. Therefore, it is location independent, and one can use such a principle to track users with decimeter accuracy without any training or mapping. One just needs to know the starting point and a map to be able to track an unlimited number of users.

In Part II, the focus is on wireless sensing and analytics. One can imagine there is a time-reversal space, and every channel impulse response has a definite focusing ball location. Let one open a door to obtain an impulse response and then close the door to have the other one. If one can tell both locations at the time-reversal space, then in essence one can tell if the door is open or closed. Chapter 6 illustrates such a basic principle for wireless event detection in indoor environments. In Chapter 7, we extend such a concept by developing a statistical model to improve robustness. Next, in Chapter 8, we further extend to recognize humans by developing radio human biometrics. The human body contains over 70% water, and therefore we all uniquely deflect/distort/absorb radio waves impinging on us in a unique way. Such a subtle difference allows us to distinguish different people. Then, in Chapter 9, we discuss how to pick up one's breathing rate from Wi-Fi signals. Even though breathing is a tiny motion, it embeds to the radio waves the periodic motion of chest movement, which can be used to estimate breathing rate. Motion is not periodic but yet can be detected as well. We show that motion detection can be done with very high accuracy and low false alarm in Chapter 10. The last chapter of this part estimates speed without any wearable devices. A statistical theory for EM waves is developed in Chapter 11 to serve as the foundation for speed estimation so that no active device is needed.

In Part III, the wireless power transfer and energy efficiency using time reversal are presented. First the energy efficiency of the time-reversal technique is shown in Chapter 12 to argue that it is ideal for green technology. In Chapter 13, we propose a new waveform called power waveforming, other than time reversal waveform, to achieve optimal wireless power transfer. Further, in Chapter 14 we extend power waveforming for multiple antenna scenarios to jointly work with beamforming to significantly improve performance.

Following the preceding discussion on indoor positioning/tracking, wireless sensing, and power transfer, one may ask if the principle of time reversal can also be leveraged for communications, especially for 5G and future generations of wireless communications. In fact, one can easily link the concepts between massive MIMO and time-reversal massive multipaths. We have seen that time reversal can produce a focusing ball by leveraging a large number of multipaths. And that is exactly what massive MIMO is doing. When there is no multipath outdoors, one has to rely on real antennas, many of them, to create "multipaths" so that by proper precoding, one can control massive MIMO to essentially produce a focusing ball at a desired location. The difference is that the time-reversal technique controls massive multipaths as virtual antennas/sensors to achieve the massive MIMO effect.

In Chapter 15, we first introduce the concept of time-reversal division multiple access, which takes advantage of the focusing effect for multiple access. Because the focusing effect has a unique strong–weak resonance effect, in Chapter 16 an adaptive algorithm is presented to combat such an effect. Then we show in Chapter 17 that the time-reversal massive multipaths effect is indeed an equivalence to the massive MIMO effect with the difference in leveraging virtual antennas. When it comes to communications, the optimal waveform is no longer the time-reversal waveform. It is because what is concerned is the signal-to-noise-ratio. Therefore, in Chapter 18, we consider waveform designs for various scenarios with a comparison to beamforming. Then in Chapter 19, we consider how the spatial focusing effect can be leveraged for networking design, and finally we introduce the tunneling effect of the time-reversal principle for the cloud radio access network.

Finally in Part V, our focus turns to how time reversal can be used to connect a large number of heterogeneous IoT devices of various bandwidths and capabilities. Chapter 21 gives an overview of how the time-reversal technique can make an impact on IoT. In Chapter 22, we illustrate that time reversal is ideal for the connection of IoT devices of various heterogeneous bandwidths and standards without any need of transcoding or complex transform.

This book is intended to be a textbook or a reference book for researchers, practitioners, or graduate students working in wireless sensing, positioning/tracking, and communications. We hope that the comprehensive coverage of the wireless AI that enables us to infer/decipher our environments and activities will make this book a useful resource for readers who want to understand this emerging technology, as well as for those who conduct research and development in this field.

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