1 Principles of Time Reversal and Effective Bandwidth

With the proliferation of Internet of Things (IoT) applications, billions of household appliances, phones, smart devices, security systems, environment sensors, vehicles and buildings, and other radio-connected devices will transmit data and communicate with each other or people, and everything will be able to be measured and tracked all the time. Among the various approaches to measure what is happening in the surrounding environment, wireless sensing has received increasing attention in recent years because of the ubiquitous deployment of wireless radio devices. In addition, human activities affect wireless signal propagations, therefore understanding and analyzing how wireless signals react to human activities can reveal rich information about the activities around us. As more bandwidth becomes available in the new generation of wireless systems, wireless sensing will make many smart IoT applications only imagined today possible in the near future. That is because when bandwidth increases, one can see many more multipaths, in a rich-scattering environment such as in indoors or metropolitan area, which can be treated as hundreds of virtual antennas/sensors. In order to control the virtual antennas and make good use of the multipaths, one can resort to the physical principles of radio propagation. Inspired by the high-resolution spatial-temporal resonance of time-reversal (TR) phenomenon, one can develop various types of wireless artificial intelligence (AI) based on the multipath channel profiles. In addition, by the spatial-temporal resonance, TR is also a good candidate platform for future 5G communications. In this chapter, we will lay out the concept of treating multipaths as virtual antennas/sensors, use the basic physical principle of TR to control them, and see how to achieve a large effective bandwidth built from smaller ones.

1.1 Introduction

With the development of wireless technologies in the era of the IoT, people are paying more and more attention to understanding the who, what, when, where, and how of everything surrounding them with wireless technologies. Human activities can affect wireless signal propagations surrounding them, and information about their activities is in turn embedded in the signals. This makes one wonder whether one can extract meaningful information through wireless sensing by analyzing various features embedded in wireless signals. By deploying wireless transceivers indoors, macro changes due to human activities and moving objects can be extracted from the wireless signals, which can help infer the real-time location of a moving object [1–8], detect an event [9–18], and facilitate applications in manufacturing asset tracking, intelligent transportation, and home/office security systems. In addition, microchanges generated by gestures [10] and vital signals [19–21] can also be captured without requiring people to wear any device, which is especially useful for providing assistance to the disabled and elderly people in smart home applications.

The performance of wireless sensing depends greatly on the richness of information that can be extracted from the radio signals, while the information richness is often dictated by the channel bandwidth through which the radio signals are transmitted. Due to the limited bandwidth in the past, only a limited number of multipaths can be seen, and not much information can be revealed in the past. With more and more bandwidth available for the next generation of wireless systems, many more smart IoT applications and services only imagined today may be possible in the near future because richer information becomes available with a wider bandwidth. For example, one can see many more multipaths indoors with a much larger bandwidth, which can serve as hundreds of virtual antennas/sensors ready to aid us for many applications.

How to control the virtual antennas to meet our needs for smart IoT applications? We have to resort to physics to do so, and TR phenomenon is a good starting point [22]. TR technique treats each path of the multipath channel as a distributed virtual antenna and provides a high-resolution spatial-temporal resonance, commonly known as the focusing effect [23–25]. In physics, the TR spatial-temporal resonance can be viewed as the result of the resonance of electromagnetic (EM) field in response to the environment [26]. When the propagation environment changes, the involved multipath signal varies correspondingly, and consequently the spatial-temporal resonance also changes. Inspired by the fundamental physical principle of TR, various types of analytics, referred to as wireless AI, can decipher radio waves to reveal the activities surrounding us. The wireless channel state information can be developed to enable many cutting-edge IoT applications that have been envisioned for a long time, but have never been achieved.

In this chapter, we will present the fundamental concept of TR. We will first discuss the impact of bandwidth on the multipath channel state information (CSI) and the principles of TR that can fully harvest the multipath CSI. Then, we discuss how to achieve a large effective bandwidth by exploiting various types of diversity.

1.2 Multipaths as Virtual Antennas

In wireless communications, when a signal emitted from a transmitter (TX) is reflected or scattered by a scatterer, an attenuated copy of the original signal is generated and reaches the receiver (RX) through a different path. The phenomenon that a signal is received by two or more paths is well known as the multipath propagation. As depicted in Figure 1.1, where each scatterer is marked by a star, the arrow from the TX directly to the RX represents the line-of-sight (LOS) path, while the other arrows represent paths reflected and scattered by scatterers. All paths together form a multipath channel between the TX and the RX [27]. As two or more copies of the original signal arrive at

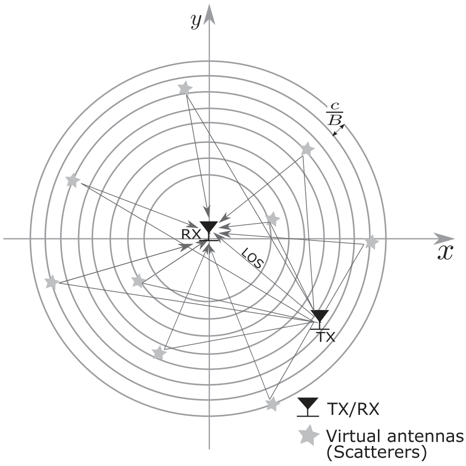


Figure 1.1 Illustration of multipath as virtual antenna.

the receiver that may be added in a noncoherent way, multipaths can cause destructive interference and degrade the performance of communication.

However, viewed from another perspective, the scatterers in the environment in fact act as virtual antennas/sensors that can be leveraged to offer some desirable outcomes. Just imagine that everyday human activities with motion and body movements affect wireless signal propagation surrounding us and thus change the channel profiles, and information about these activities is embedded in the signals. When signals are bounced back and forth by the scatterers, multiple "replicas" are generated, which contains enriched meaningful information about our activities. Each of such multipaths is in essence a degree of freedom naturally existing in our surrounding environment. They can be considered as tens or hundreds of virtual antennas ready to serve us on demand. In other words, our environment provides a high degree of freedom by means of radio multipath propagations, ready for our uses.

Now how do we harvest multipaths? The transmission power and bandwidth are two key components to consider [28, 29]. On the one hand, increasing the transmission power leads to a higher signal-to-noise ratio (SNR) and thus more observable multipath components. On the other hand, the spatial resolution in resolving independent multipath components is determined by the transmission bandwidth. Due to the limited bandwidth, which is equal to the channel sampling rate, the multipaths with propagation delay difference less than a channel sampling period T_{sample} will merge into a single tap. Thus, as noted in Figure 1.1, the resolution to separate radio paths with different lengths in a multipath propagation is limited to $cT_{sample} = c/B$, with c being the speed of light and B being the bandwidth. Therefore, the larger the bandwidth, the better the spatial resolution and thus the more multipaths can be resolved. An example of multipath channel profiles captured under different bandwidths from LTE, Wi-Fi, and the entire ISM 5 GHz band, at the same location in a rich-scattering environment is demonstrated in Figure 1.2. When the bandwidth is 20 MHz (as in LTE), only 5

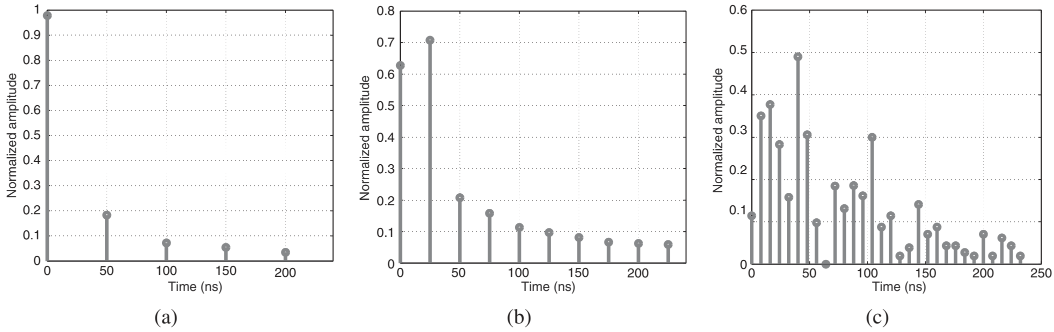


Figure 1.2 Multipath channel vs. bandwidth. (a) Measured channel under 20 MHz bandwidth (LTE standard). (b) Measured channel under 40 MHz bandwidth (the IEEE 802.11n standard). (c) Measured channel under 125 MHz bandwidth (entire ISM 5 GHz band) [27]. We first measure a sample channel impulse response in a typical indoor environment us ing a time-reversal prototype [30] with a bandwidth of 125 MHz in the ISM 5 GHz band. Then different filters with a bandwidth of 20 MHz, 40 MHz, and 125 MHz, respectively, are applied to the measure channel profile. For a linear time-invariant system, the filtering operation on the receiver side is equivalent to that on the transmitter side. Therefore, the filtered channel impulse response is equivalent to that measure with the same bandwidth as the filter.

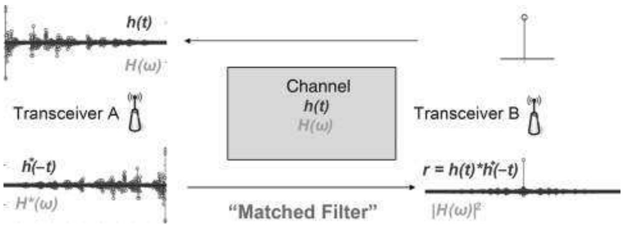


Figure 1.3 The time-reversal signal processing principle.

multipaths can be resolved; when the bandwidth increases to 40 MHz (as in Wi-Fi) about 10 multipaths can be resolved. When the bandwidth further increases to 125 MHz, around 30 multipaths with clear details of difference can be resolved, which clearly shows an increasing number of multipaths as bandwidth increases.

How to utilize the multipaths as virtual antennas/sensors? We find that a good starting point is to resort to the physics of TR and its focusing effect. As shown in Figure 1.3, in TR with two transceivers A and B, transceiver B first sends a channel probing signal (e.g., an impulse) to transceiver A, at which the multipath channel state information (CSI) [31] can be estimated. Then transceiver A time-reverses (and conjugates if the signal is complex) the received waveform and transmits the time-reversed version of waveform back to transceiver B. It has been well known [25–28] that the convolution of the time-reversed waveform and the channel can generate a unique peak at the specific receiver's location, called the spatial focusing effect (more details will be discussed in the next section). This indicates that the multipath channel profile works as a unique and location-specific signature, and the spatial focusing effect only happens when the channel can "match" the time-reversed waveform. By comparing the multipath CSI with a set of time-reversed CSI precollected at multiple known locations, one can infer the current location of a device, and this idea can be applied to assist positioning. Because this works for both line-of-sight and non-line-of-sight conditions, it is as if the notion of walls and obstacles of indoors has disappeared. That has been well captured in the CSI.

Because each multipath profile is in essence a focusing point on the "time-reversal logical space," if an event happens such as a door opens or closes that affects the multipath, as a result the multipath profile is now mapped to another focusing point. If one can perform analytics or machine learning to distinguish both events, then one shall be able to infer what has happened. With this notion, one can further design various types of analytics based on the multipath CSI, which we refer to as *wireless AI*. By fully exploiting the rich multipath CSI, wireless AI can decipher the propagation environment, reveal subtle information on various human activities, as if a new extended sixth human sense. Wireless AI can enable many cutting-edge IoT applications, such as accurate indoor positioning, tracking, wireless event detection, human recognition, vital signs monitoring, wireless power transfer, and 5G communications, as we will illustrate in this book.

1.3 Time-Reversal Principle

TR is a fundamental physical phenomenon that takes advantage of the unavoidable but rich multipath radio propagation environment to create a spatial-temporal resonance effect, the so-called focusing effect. Let us imagine that there are two points, A and B, within the space of a metal box. When A emits a radio signal, its radio waves bounce back and forth within the box, some passing through B. After a certain time, the energy level decreases and is no longer observable. Meanwhile, B can record the multipath profile of the arriving waves as a distribution in time. Then, such a multipath profile is time reversed (and conjugated) by B and emitted accordingly, the last first and the first last. With channel reciprocity, all the waves, following the original paths, will arrive at A at the same particular time instant, adding up in a perfectly constructive way. This is called the focusing effect. In essence, it is a resonance effect taking place at A stimulated by B using the time-reversed multipath profile through the interaction with the box as demonstrated in Figure 1.4. Mathematically, the TR effect is simply for the environment to serve as the computer to perform a perfect deconvolution; in essence, the environment behaves like a matched filter.

The spatial focusing effect of TR is fundamentally due to the decreased correlation between the channel states of two different locations. As discussed in the previous section, the multipaths can be viewed as virtual antennas, and as the transmission bandwidth increases, more multipaths can be resolved in a rich scattering environment. By utilizing the TR technique, the signal energy can concentrate on an intended location. On the other hand, the massive number of (physical) antennas in a massive MIMO (multiple-input, multiple-out) system can create the CSI with a large dimension for each

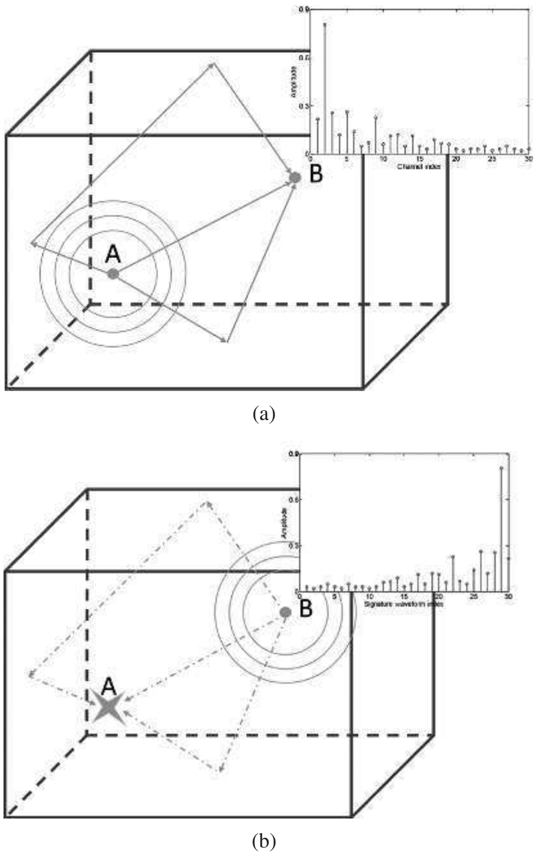


Figure 1.4 An illustration of time reversal: (a) channel probing phase and (b) data transmission and focusing phase.

location. By utilizing a matched filter-based precoder or equalizer, the signal energy can also concentrate on a corresponding location [32].

To illustrate the spatial focusing effect of both systems with different bandwidth/ number of antennas, we conduct a simulation based on ray-tracing techniques in a discrete scattering environment. As shown in Figure 1.5, 400 scatterers are distributed randomly in a $200\lambda \times 200\lambda$ area, where λ is the wavelength corresponding to the carrier frequency of the system. The wireless channel is simulated by calculating the sum of the multipaths using the ray-tracing method given the locations of the scatterers. Without loss of generality, we use a single-bounce ray-tracing method to calculate the channels for both the TR system and the massive MIMO system on the 5 GHz ISM band. We select the reflection coefficients of the scatterers to be i.i.d. complex random variables with uniform distribution in amplitude $[0, 1]$ and phase $[0, 2\pi]$. For the massive MIMO system, the linear array is configured with the line facing the scattering area, and the interval between two adjacent antennas is $\lambda/2$. The distance from the transmitter and the intended location is chosen to be 500λ for both systems.

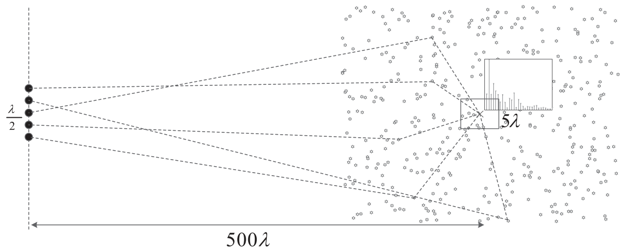


Figure 1.5 Simulation setup for validating spatial focusing effect.

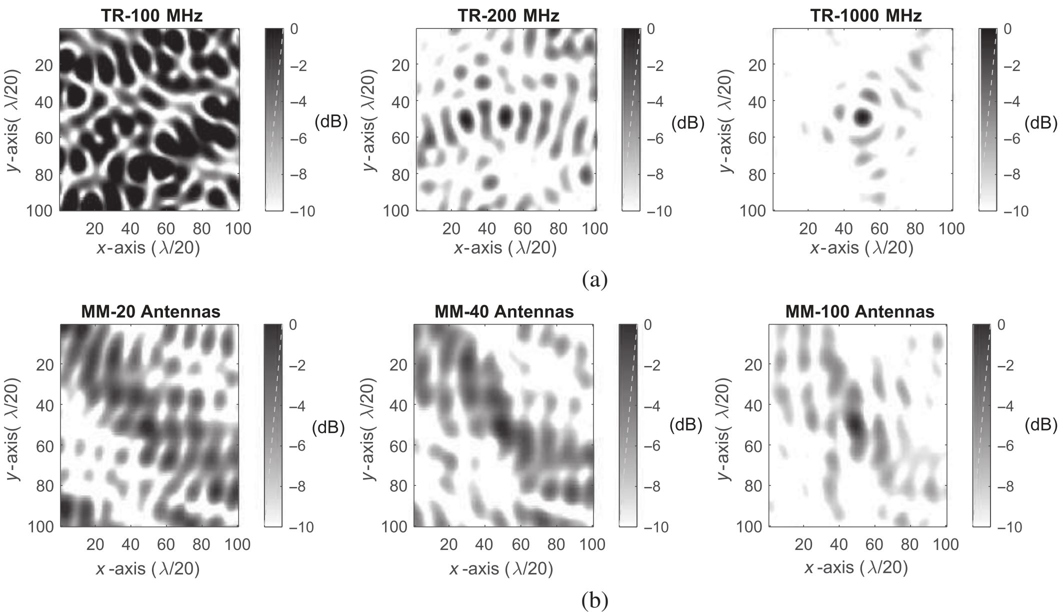
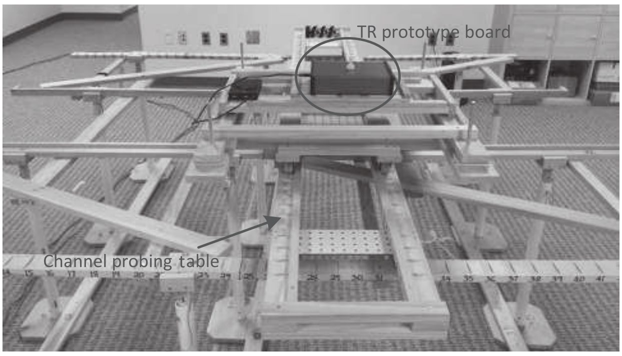


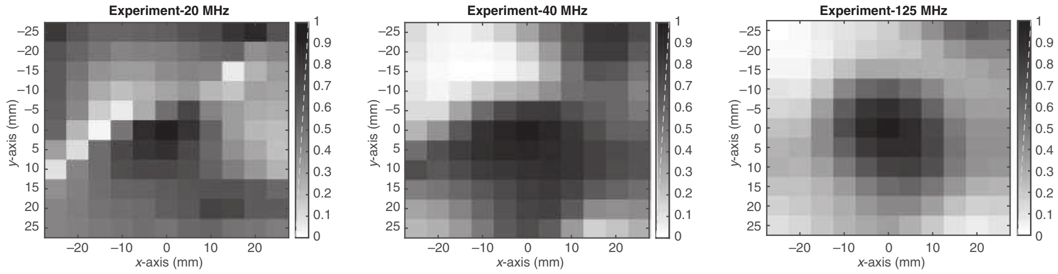
Figure 1.6 Spatial focusing effect of both systems: (a) TR wideband system and (b) massive MIMO system.

In the simulations, we adjust the transmitting bandwidth of the TR system and the number of antennas in the massive MIMO system to show their impact on the spatial focusing effect. The transmitter of the TR system transmits with bandwidths ranging from 100 MHz to 1 GHz with one antenna, where a wider bandwidth can resolve more CSI taps and increase the degree of freedom of the system. The number of antennas in the massive MIMO system is selected from 20 to 100 with bandwidth fixed at 1 MHz in the simulation. We select the matched filter waveform and beamforming weights in the TR system and the massive MIMO system, respectively.

We consider the received energy strength in a $5\lambda \times 5\lambda$ area around the location of the intended user. Figure 1.6 shows the simulation results for both systems with a single realization of the channel and scatterer distribution, and we normalize the maximum received energy to 0 dB. We can see that the energy focusing effect becomes more obvious at the intended location with the increase in the bandwidth and the number of



(a)



(b)

Figure 1.7 Spatial focusing effect of TR wideband system prototype: (a) TR wideband system prototype and (b) experiment results.

antenna, which is the result of a larger degree of freedom to concentrate the energy only at the intended location.

To further verify the spatial focusing effect, we built a prototype of TR wideband system on a customized software-defined radio (SDR) platform, as shown in Figure 1.7(a). The hardware architecture combines a specific designed radio-frequency board covering the ISM band with 125 MHz bandwidth, a high-speed Ethernet port, and an off-the-shelf user-programmable module board. In this experiment, we measure the CSIs of a square region with a dimension of 5 cm $\times$ 5 cm on a channel probing table, which is located in a typical office environment as shown in Figure 1.7. The intended location is chosen to be the center of the measured region, and the corresponding normalized field strength is shown in Figure 1.7(b). We can see that the TR transmission can generate a clear energy focusing around the intended location, even under a not-so-wide bandwidth of 125 MHz.

The research of TR dates back to the 1950s, where TR was utilized to compensate the phase-delay distortion that appears during long-distance transmissions of slow-speed pictures over telephone lines [33]. It has also been used to design noncausal recursive filters to equalize the ghosting artifacts of analog television signals caused by multipath propagation [34].

It was observed in a practical underwater propagation environment [35] that the energy of the TR acoustic waves from transmitters could be refocused only at the intended location with very high spatial resolution. The spatial and temporal focusing feature can also be used for radar imaging and acoustic communications. Note that the resolution of spatial and temporal focusing highly depends on the number of multipaths. To be able to harvest a large number of multipaths, large bandwidth and thus high sampling rate is required, which was difficult or even impossible to achieve in the past. Fortunately, with the advance of semiconductor technologies, broadband wireless technology has become available in recent years, and exploiting TR effect has also become possible in wireless radio systems. Experimental validations of the TR technique with electromagnetic (EM) waves have been conducted [36], including the demonstration of channel reciprocity and spatial and temporal focusing properties. Combining the TR technique with ultra-wideband (UWB) communications has been studied with the focus on the bit error rate (BER) performance through simulations [37]. A system-level theoretical investigation and comprehensive performance analysis of a TR-based multiuser communication system was conducted [38], where the concept of time-reversal division multiple access (TRDMA) was proposed. Also, a TR radio prototype was built to conduct TR research and development [39].

When applying the TR technique in wireless communications, if the transmitted symbol duration is larger than (or equal to) the channel delay spread, the time-reversed waveform can guarantee the optimal BER performance by virtue of its maximum signal-to-noise ratio (SNR) property. However, if smaller, which is generally the case in high-speed wireless communication systems, the delayed versions of the transmitted waveforms will overlap and thus interfere with each other. Such intersymbol interference (ISI) can be notably severe and cause crucial performance degradation, especially when the symbol rate is very high. The problem becomes even more challenging in a multiuser transmission scenario, where the interuser interference (IUI) is introduced due to the nonorthogonality of the channel impulse responses among different users. To address this problem, one can utilize the degrees of freedom provided by the environment, i.e., the abundant multipaths, to combat the interference using signature waveform design techniques. The basic idea of signature waveform design is to carefully adjust the amplitude and phase of each tap of the signature waveform based on the channel information such that the signal at the receiver can retain most of the useful signal while suppressing the interference as much as possible. Moreover, with random scatterers, TR can achieve focusing that is far beyond the diffraction limit [40], which is half wavelength.

1.4 Principle of Effective Bandwidth

As discussed earlier in this chapter, the multipath channel profile works as a unique and location-specific signature/or fingerprint, and the spatial focusing effect only happens when the channel can “match” the time-reversed waveform. By comparing the multipath CSI with a set of time-reversed CSI precollected at multiple known locations, one can infer the current location of a device, and this idea can be applied to assist positioning.

However, as the maximum bandwidth in mainstream Wi-Fi devices is only either 20 or 40 MHz, bandwidth limitation becomes the main reason that prevents the forming of a clear and precise spatial focusing effect. As shown in Figure 1.7(b) with 20 or 40 MHz bandwidth, there is no obvious spatial focusing effect, and a large region of nearby locations is ambiguous with the target location. Enlarging the bandwidth shrinks the area of ambiguous regions. When the bandwidth increases to 125 MHz, the ambiguous region is reduced to a ball of 1 cm radius, which implies centimeter accuracy in localization. The experiment results motivate us to formulate a large effective bandwidth by exploiting diversities to facilitate high-accuracy indoor localization and other wireless AI based on CSI fingerprints. In this following, we will discuss the concept of effective bandwidth and how to achieve a large effective bandwidth using Wi-Fi positioning as an example.

To characterize the similarity between CSIs collected at the same or different locations, the time-reversal resonating strength (TRRS) of the focusing effect can be defined as [41]

$$\gamma[\mathbf{H},\mathbf{H}'] = \left(\frac{\eta}{\sqrt{\Lambda}\sqrt{\Lambda'}}\right)^2, \tag{1.1}$$

with

$$\eta = \max_{\phi} \left| \sum_{k=1}^{K} H_k H_k'^{*} e^{-jk\phi} \right|, \quad \Lambda = \sum_{k=1}^{K} |H_k|^2, \quad \Lambda' = \sum_{k=1}^{K} |H_k'|^2, \tag{1.2}$$

where $\mathbf{H}$ and $\mathbf{H}'$ represent two fingerprints, K is the total number of usable subcarriers, H_k and H_k' are the CSIs on subcarrier k, η is the modified cross-correlation between $\mathbf{H}$ and $\mathbf{H}'$ with synchronization error compensated, and Λ, Λ' are the channel energies of $\mathbf{H}$ and $\mathbf{H}'$, respectively. Realizing that the Wi-Fi receiver may not be fully synchronous with the Wi-Fi transmitter due to mismatches in their radio-frequency front-end components [42], an additional phase rotation of $e^{-jk\phi}$ is employed to counteract the phase distortions incurred by the synchronization errors in the calculation of η, where ϕ can be estimated and compensated using Algorithm 1, shown later. Equation (1.1) implies that TRRS ranges from 0 to 1. More specifically, a larger TRRS indicates a higher similarity between two CSIs and thus the two associated locations.

1.4.1 Increasing Effective Bandwidth via Diversity Exploitation

Two different diversities exist in the current Wi-Fi system, i.e., frequency diversity and spatial diversity. According to IEEE 802.11n, 35 Wi-Fi channels are dedicated to Wi-Fi transmission in 2.4 GHz and 5 GHz frequency bands with a maximum bandwidth of 40 MHz. The multitude of Wi-Fi channels leads to frequency diversity in that they provide opportunities for Wi-Fi devices to perform frequency hopping when experiencing deep fading or severe interference. On the other hand, spatial diversity can be exploited on multiple-input-multiple-out (MIMO) Wi-Fi devices, which is a mature technique that greatly boosts the spectral efficiency. MIMO has not only become an essential component of IEEE 802.11n/ac but has also been ubiquitously deployed on numerous commercial Wi-Fi devices. For Wi-Fi systems, both types of diversity can be harvested to provide a fingerprint with much finer granularity and thus lead to less ambiguity in comparison with the fingerprint measured with a bandwidth of only 40 MHz.