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Why Time Reversal for Future 5G Wireless?

Editors' Note

Several influential magazines from sister Societies of the IEEE and other technical or scientific associations regularly publish commentary sections that present analysis by technical or policy experts on issues of interest to the readers. These commentaries complement existing editorials and offer readers valuable perspectives on a broader range of issues.

Inspired by the values of these commentaries, we are initiating a new column for *IEEE* Signal *Processing Magazine* (*SPM*) called "Perspectives," which highlights an area of recent exciting research and projects its potential technological impact to our everyday lives. Different from a feature article or other existing technical columns of *SPM*, this "Perspectives" column offers an outlook of an author or group of authors, as backed by technical evidences available thus far.

In this first "Perspectives" column article, Chen et al. present a brief overview and their technical opinions on the prospects of time-reversal (TR) techniques in the fifth-generation (5G) wireless communications based on their survey of the literature as well as their firsthand, cutting-edge research that has been transferred into the early stages of practice.

It is possible that, after seeing the same technical evidences and perhaps having access to additional evidences, other experts may have different opinions. We welcome readers' feedback toward the "Perspectives" column articles, and we will be happy to share your comments with the authors. Your comments may be used to help us initiate future articles in this new column, organize forum discussions, or evolve into articles for the eNewsletters.

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As the demand for wireless voice and data services has continued to grow dramatically, operators struggle to satisfy this demand with acceptable quality of service. The main approach until now was to increase the system bandwidth and spectral efficiency. For instance, there was an almost tenfold increase for each new generation of cellular technology [the first generation (1G) technology can support up to 30 kHz, second generation (2G) around 200 kHz, third generation (3G) around 1.25–5 MHz, and fourth generation (4G) up to 20 MHz]. Meanwhile, technologists have begun seeking more innovative and efficient communication technologies to meet the ever-increasing demand for data traffic with advanced signal processing capabilities for the 5G wireless communication systems. It is expected that 95% of data traffic will come from indoor locations in a few years [1]. Compared to outdoor propagation, wireless medium in an indoor environment often exhibits richer multipath propagation mostly without a strong line-of-sight (LOS) component, which makes the design of 5G indoor communication systems even more challenging.

Several key ideas have received attention as promising candidates for future 5G wireless communication systems in recent years. The first candidate solution is the massive multiple-input, multiple-output (MIMO) technique [2]. The massive MIMO effect, in essence, makes the channels to different users quasiorthogonal with very simple spatial multiplexing/demultiplexing procedures and achieves large spectral efficiency gains [3]. A straightforward approach to implement this technique is to mount hundreds of antennas on the transmitter and/or the receiver. However, challenges such as pilot contamination, hardware implementation complexity, antenna correlation, and mutual coupling due to the large number of antennas have to be carefully addressed. In addition, the requirement of deploying a large number of antennas at the base station in massive MIMO systems may not be feasible in indoor scenarios.

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The second candidate solution is network densification by more heterogeneous network deployment, such as the small cell technique and device-to-device (D2D) communication technique [4]. These techniques can improve the link efficiency by replacing longer links with shorter ones. However, coordination and interference management among the small cells (or D2D links) may become challenging. Ideally, the network should be easily scalable so that when additional cells/links are needed, little interference will be introduced, requiring only low-complexity interference management.

Another candidate solution is the cloud-based radio access networks (C-RAN) [5], where all the baseband processing is carried out through high-performance computing in a centralized structure, which transforms the evolution of the wireless networks from today's cell-centric architecture into a device-centric architecture [3]. Nevertheless, as with network densification, the limited fronthaul link capacity may prevent the C-RAN from fully utilizing the benefits made possible by concentrating the processing intelligence at the cloud.

Besides the aforementioned challenges of the candidate techniques, the operation of a large number of base stations and heterogeneous devices will consume a lot of energy. Therefore, the next-generation networks should focus on achieving better energy efficiency and reduce the complexity of user devices as much as possible.

From the aforementioned discussion, we can see that most of the existing solutions for 5G have their inherent limitations, which may make them either difficult to implement as a collectively cohesive solution or not as efficient as expected. Moreover, these solutions may not work well in indoor environments, where the vast majority of current and future data traffic will come from. In this article, we will show that TR communication possesses many outstanding characteristics to address most of the previously mentioned challenges and, therefore, is an ideal candidate platform for 5G indoor systems.

What is the TR phenomenon?

Time reversal (TR) is a fundamental physical phenomenon that takes advantage of an 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 reduces 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 of 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.

One can imagine that the larger the transmission power, the more bouncing back and forth of the electromagnetic (EM) waves in the box, and, therefore, the more observable multipaths. When the power is fixed, so is the maximum number of observable multipaths. Since radio waves travel at the speed of light, for one to see the multipath profile in detail, it needs high resolution in time, which implies very broad bandwidth in frequency. The larger the bandwidth, the better the time resolution, and, therefore, the more multipaths can be revealed. Essentially, multipaths are naturally existing degrees of freedom ready to be harvested via transmission power and bandwidth.

In a real environment, especially indoors, depending on the structure of the buildings, the number of observable multipaths is limited due to the power of the radio and its bandwidth. Still, one can observe around 15–30 significant multipaths with 150-MHz bandwidth—the entire Industrial Scientific Medical (ISM) band at 5.8 GHz. Such a large number of degrees of freedom that exist

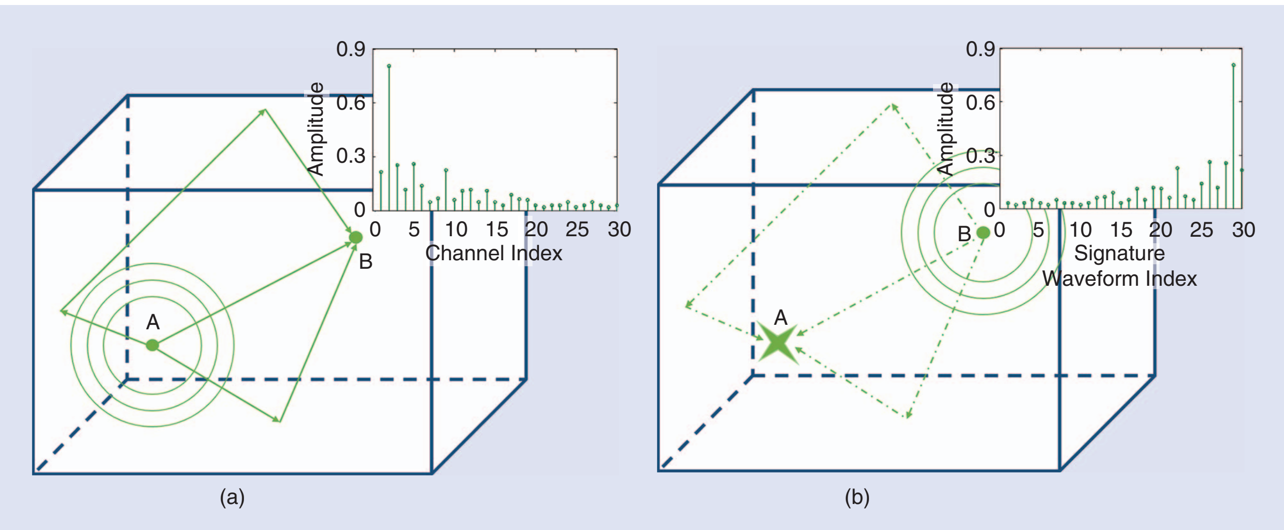
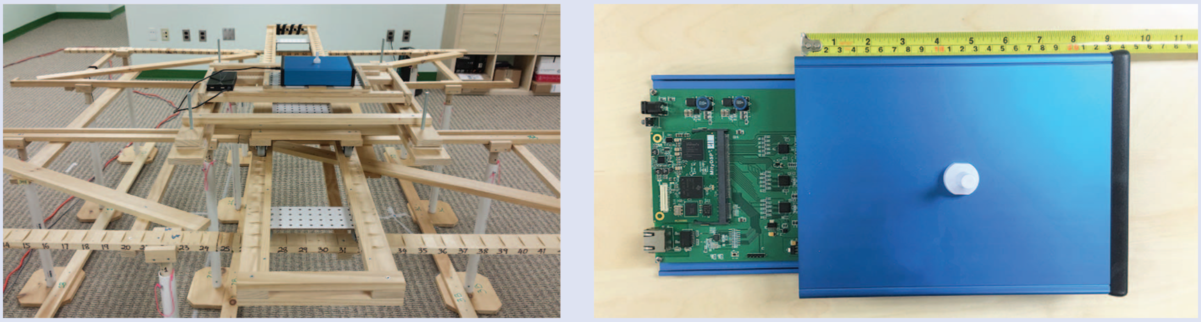


FIGURE 1. An illustration of TR: (a) the channel probing phase and (b) the data transmission and focusing phase.



(a) (b)

FIGURE 2. An example of the TR prototype: (a) three-dimensional (3-D) architecture for collecting measurements and (b) details of the prototype. (Figure courtesy of Origin Wireless, Inc.)

in nature can be harvested to enable engineering applications.

Brief history of TR

Mathematically, the TR effect is simply for the environment to serve as the computer to perform a perfect deconvolution; that is, the environment behaves like a matched filter! 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 [6]. It has also been used to design noncausal recursive filters to equalize the ghosting artifacts of analog television signals caused by multipath propagation [7].

It was observed in a practical underwater propagation environment [8] 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 a 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 the TR effect has also become possible in wireless radio systems. Experimental validations of the TR technique with EM waves have been conducted [9], including the demonstration of channel reciprocity and spatial and temporal focusing properties. Combining the TR technique with ultrawideband (UWB) communications has been studied with the focus on the bit error rate (BER) performance through simulations [10]. A system-level theoretical investigation and comprehensive performance analysis of a TR-based multiuser communication system was conducted [11], where the concept of TR division multiple access was proposed. Also, a TR radio prototype was built to conduct TR research and development [12]. As shown in Figure 2, the TR prototype is a customized software-defined radio platform for designing and deploying TR-based communication systems. The hardware architecture combines a specific designed radio-frequency (RF) board covering the ISM band with 125-MHz bandwidth, a high-speed Ethernet port, and an off-the-shelf user-programmable MityDSP-L138F module board (containing ARM9, floating point DSP, and Xilinx Spartan-6 FPGA). The size of the radio is $5\,\text{cm} \times 17\,\text{cm} \times 23\,\text{cm}$, the weight is about 400 g, and the power consumption is 25 W. As a comparison, the size, weight, and power consumption of the massive MIMO prototype at Lund University in Sweden [13] is $0.8\,\text{m} \times 1.2\,\text{m} \times 1\,\text{m}$, 300 kg, and 2.5 kW, respectively.

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 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

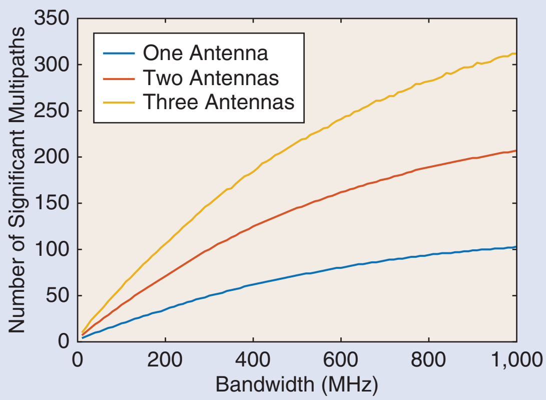


FIGURE 3. The number of significant multipaths at different bandwidths.

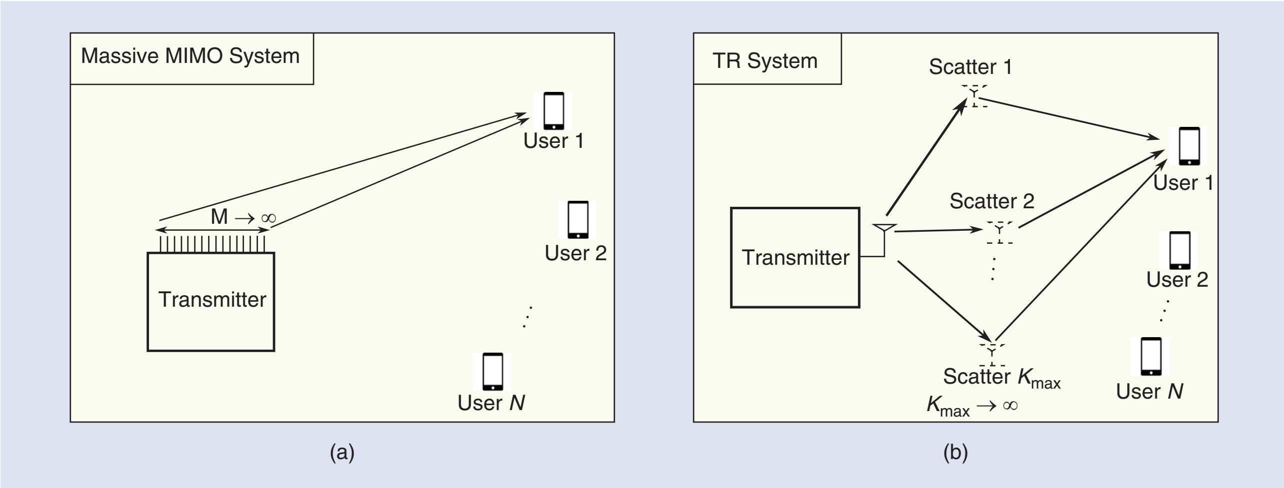


FIGURE 4. Two different ways of realizing a massive MIMO effect: (a) the multiantenna approach and (b) the TR approach.

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 [14], which is a half wavelength.

TR effects

In this section, we argue that TR is an ideal platform for future 5G wireless communication systems because it can realize a massive MIMO-like effect using a single antenna and has low complexity, as the environment is serving as the computer. It is highly energy efficient, scalable for extreme network densification, and ideal for cloud-based radio access networks. It also offers, in a simple way, very high-resolution localization performance for indoor positioning systems, an essential property for Internet of Things (IoT) applications. TR communication meets all the requirements one can envision for future 5G wireless!

A single-antenna realization of massive MIMO effect

In a typical indoor environment, the reflection, diffraction, and scattering in the wireless medium due to the various obstacles and reflectors—such as walls, windows, and furniture—often create a large number of multipath components. As new spectrum and larger bandwidth become available, more rich-scattering multipaths can be revealed. But how many multipaths can be harvested? To answer that, we used two universal software radio peripherals as channel sounders to probe the real channel in an office environment. Specifically, we scanned the spectrum from 4.9 to 5.9 GHz to acquire the channel impulse response with a bandwidth of 10 MHz–1 GHz using transmission power of 100 mW. Based on these experiments, we show in Figure 3 the number of significant multipaths in an indoor environment versus the channel bandwidth. It can be seen that, with a single antenna, the number of multipaths can approach approximately 100 as the bandwidth increases to 1 GHz. Such degrees of freedom can be further scaled up by deploying more antennas.

Different from the way conventional techniques exploit the multipath propagation environment—e.g., orthogonal frequency-division multiplexing (OFDM) exploiting the multipath components as frequency diversity and code-division multiple access using the Rake receiver to coherently combine the multipath components—the TR technique can take advantage of the multipath propagation without the need for deploying complicated receivers or a large number of antennas if sufficiently large bandwidth can be used. The larger the bandwidth, the better the resolution of individual multipath components. As shown in Figure 4(a) and (b), there are two ways to realize the massive MIMO effect. One is to use a large number of real antennas to straightforwardly

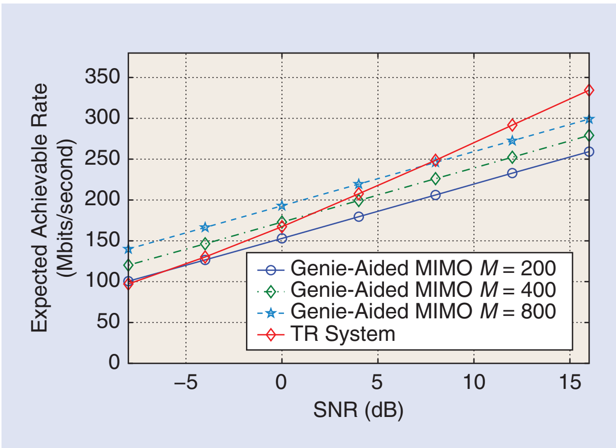


FIGURE 5. Expected achievable rate comparison between a massive MIMO system and the TR system.

build a massive antenna system. And the other is to leverage TR that inherently treats the multipaths in the environment as virtual antennas. Both can achieve the spatial-temporal resonance at a particular space and time that we now commonly term as the massive MIMO effect. Basically, it is a small focusing ball of energy that takes place due to the very high degree of freedom.

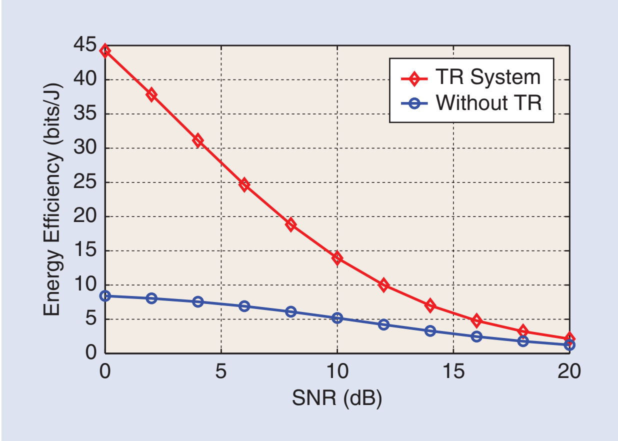


FIGURE 6. A comparison of energy efficiency between a TR system and direct transmission without TR.

Therefore, by exploiting a large number of virtual antennas, a single-antenna TR system can achieve superior focusing effect in both time and spatial domains, resulting in similar promising performance as massive MIMO systems. In addition, the implementation complexity of a TR system is much lower since it utilizes the environment as a virtual antenna array and a computing resource. If cooperation of users, e.g., cooperative communications, is a distributed way of achieving the MIMO effect of high diversity, then TR is similarly a cooperation of virtual antennas to achieve the massive MIMO effect. The TR waveform is nothing but to control each multipath (virtual antenna). Of course, what cooperation pays for is the spectral efficiency due to the use of time for distributed processing, in return for the diversity effect.

In Figure 5, the performance comparison is shown in terms of the expected achievable rate between a practical TR system and an ideal genie-aided massive MIMO system. The expected achievable rate is computed by averaging the achievable rate defined in [15] over different channel realizations. By genie aided, we mean an ideal condition that the interference and antenna coupling effects in the massive MIMO system can be completely eliminated with optimal beamforming. The genie-aided massive MIMO system has M transmit antennas with 20-MHz bandwidth where M is in the order of hundreds [13], while the TR system has a single transmit antenna with 1-GHz bandwidth. It is assumed that there are ten users in both systems, each equipped with a single antenna. In other words, the massive MIMO system we considered here is a multiuser MIMO (MU-MIMO) system [2]. The total transmit power is set to be the same for both systems. The overhead of both systems mainly comes from the channel acquisition, and thus is similar. From Figure 5, it can be seen that, at the cost of a larger bandwidth, the TR system can achieve comparable if not better rates with the genie-aided massive MIMO system by using only a single antenna. This is achieved through exploiting a large number of virtual antennas that naturally exist in the environment. Note that the performance of the TR system was obtained from real data, while that of massive MIMO is the best case scenario. Also note that the massive MIMO system requires a large number of antennas that is suited for high-power outdoor base stations, while the TR system leverages large bandwidth to harvest naturally existing multipaths, ideal for low-power indoor applications.

Energy efficiency

TR technology can take advantage of the multipath propagation and achieve good energy efficiency. The temporal focusing effect concentrates a large portion of the useful signal energy of each symbol within a short time interval, which effectively reduces the ISI for high-speed broadband communications. The spatial focusing effect allows the signal energy to be harvested at the

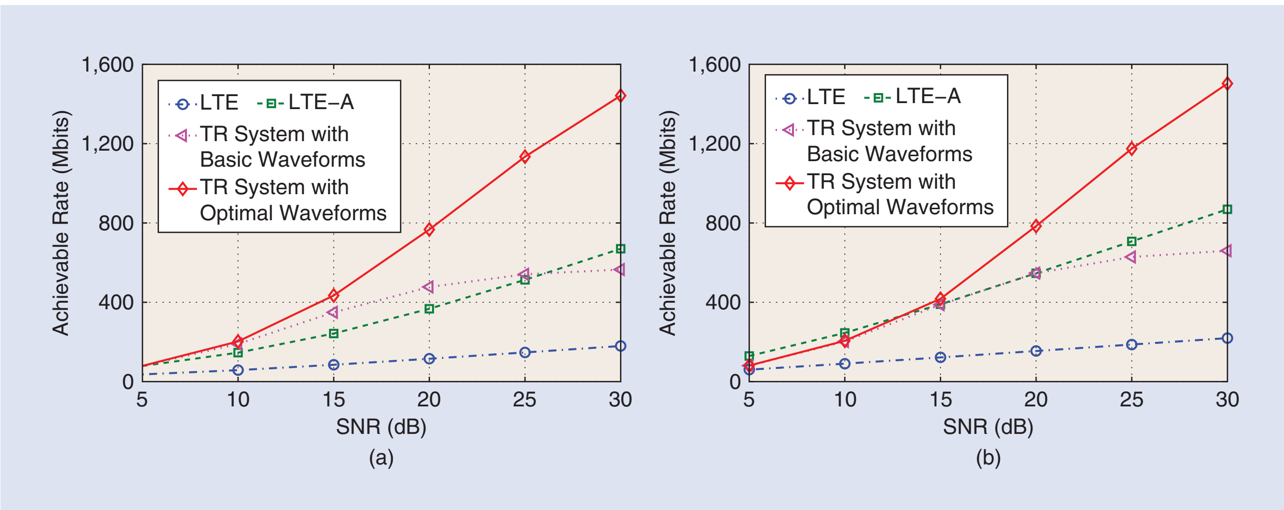


FIGURE 7. An achievable rate comparison: (a) one user case and (b) ten users case.

intended location and reduces leakage to other locations, leading to a reduction in both the required transmit power consumption and cochannel interference to other locations.

Defining energy efficiency (in bits/Joule) of a system as the spectral efficiency (sum-rate in bits/channel use) divided by the transmit power expended (in Joules/channel use), and using real-world channel measurements in a typical indoor environment, we compare the energy efficiency of a TR system with that of a direct transmission system without TR. The results are shown in Figure 6. It can be seen that with TR, the energy efficiency can be improved by up to 7 dB. Note that a wide bandwidth is generally required for a TR system to resolve the rich multipaths and fully harvest energy from the environment. As 5G technology is expected to be able to support larger bandwidth, the benefits and unique advantages of TR due to the temporal and spatial focusing effects in a rich-scattering environment promise a great potential for achieving high energy-efficiency in next-generation networks.

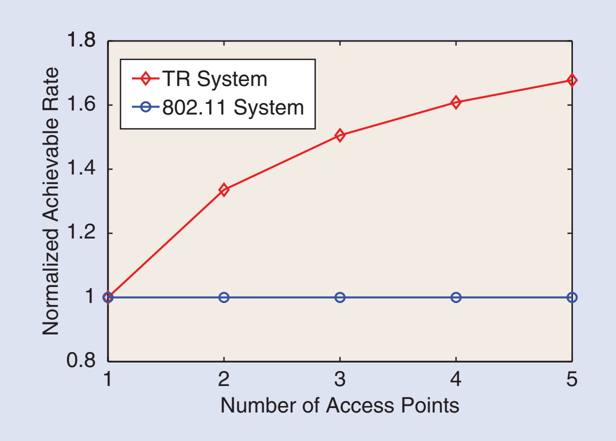


FIGURE 8. The normalized achievable rate comparison between the TR system and 802.11 system.

High capacity when bandwidth is available

By utilizing spatial focusing, a TR access point (AP) can communicate with multiple users simultaneously within the same spectrum, i.e., the spectrum is fully reused by different users. Such a full spectrum reuse feature, together with wide bandwidth, have the potential to provide high capacity [15]. This is validated in Figure 7, where we show the performance comparison in terms of achievable rate between the TR system and two OFDM systems.

It can be seen that for the one-user case, even with basic TR waveform, the TR scheme can achieve much better performance than long-term evolution (LTE) in all SNR regions and better performance than LTE-advanced (LTE-A) in most SNR regions. With optimal waveform, the performance of the TR system can be further improved. When there are ten users, due to the selectivity among different users, the achievable rate of LTE and LTE-A can be enhanced, and LTE-A can achieve comparable and even slightly better performance than the TR system with basic TR waveform. Nevertheless, with optimal waveform, the TR system can still outperform LTE and LTE-A in most SNR regions, which demonstrates that the TR system can achieve higher capacity than OFDM systems when the bandwidth is wide enough. Note that there is a large amount of spectrum at millimeter-wave frequencies [3] that can be utilized by TR.

Scalability for extreme network densification

With a high capacity, a single TR AP has the potential to serve many users while creating little interference to other wireless users. However, in some scenarios, the density of users may be so high that one single AP is insufficient to support all of them. We will show that the TR system is highly scalable and extra APs can be added with simple reconfiguration.

In conventional wireless communication systems, a mechanism is needed to prevent or alleviate the interference introduced by adding more APs due to the near-far effect. This near-far effect is solely the result of the distance between the AP and the users. In the TR system, however, different users have different resonances, which are the result of location-specific channel impulse responses instead of the distance only. With such a strong-weak focusing effect, there is no clear definition of

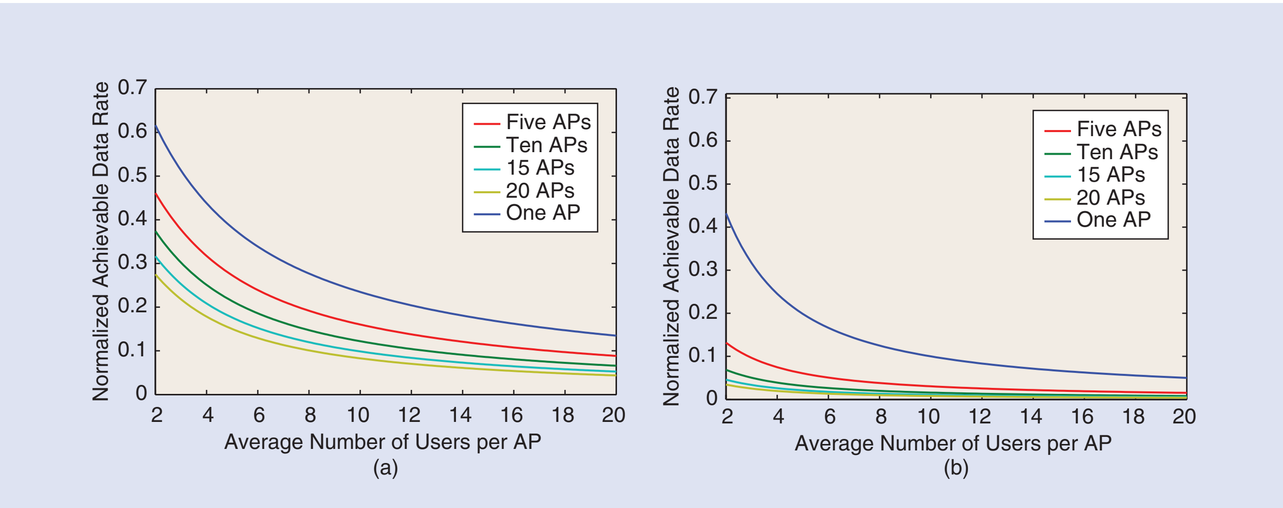


FIGURE 9. A comparison between the TR system and 802.11 system: (a) graceful performance degradation of TR and (b) performance degradation of 802.11.

cell boundaries. Thus, the TR system has a simple reconfiguration property, allowing the easy addition of new APs to the system. The newly added APs in the TR system help pick up users and reuse the same spectrum without incurring much interference, while in conventional systems, intercell radio resource management is needed to coordinate resource allocation between different cells and to limit the intercell interference. Such a self-configuring feature provides native support for machine-to-machine (M2M) and D2D communications where multiple pairs of machines/devices can coexist and share the spectrum without complicated transmission coordination strategies.

Figure 8 shows the performance comparison in terms of normalized achievable rate versus the number of APs, where the normalization is performed over the achievable rate of the single AP case. It can be seen that the normalized achievable rate of conventional systems remains unchanged regardless of the increase of the number of APs. This is because neighboring APs cannot use the same resource in conventional systems due to the interference. On the other hand, with the TR system, by utilizing the spatial focusing effect, all APs use the same spectrum and thus the normalized achievable rate increases as the number of APs increases. Note that although different APs share the same spectrum, they are nearly orthogonal with each other. In traditional systems, such orthogonality can only be achieved by applying additional techniques, such as time, code, or frequency division multiplexing. In the TR system, this near-orthogonality is achieved naturally by utilizing the large number of multipath components in the wireless channel.

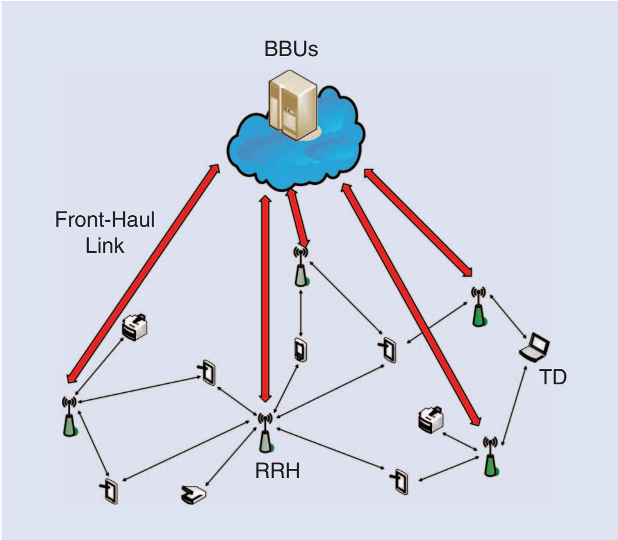


FIGURE 10. The C-RAN architecture.

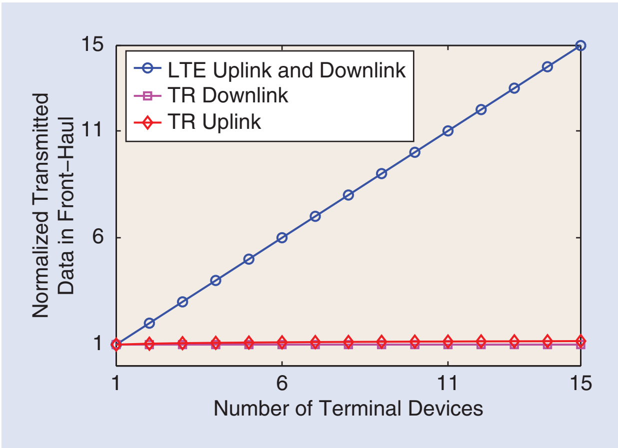


FIGURE 11. A comparison of the normalized total transmitted data in a fronthaul between TR-based and LTE-based C-RAN.

The performance degradation of each individual user is shown in Figure 9, where the normalization is over the point-to-point link capacity. It can be seen that the performance degradation of the IEEE 802.11 system is much more severe than the TR system. This is because each link in 802.11 requires an exclusive use of the channel, which is inefficient if there are many users/APs close to each other. On the contrary, the TR system can tolerate interference through the interference mitigation effect of TR so that multiple users/APs can share the same spectrum. Therefore, the performance degradation is more graceful, and each user is more robust against the interference from nearby users/APs.

Ideal for cloud-based networking

In most of the current C-RAN structures as shown in Figure 10, the fronthaul link capacity between the baseband units (BBUs) and the distributed remote radio heads (RRHs) often becomes a bottleneck when there are a large number of users/terminal devices (TDs) in the network. Several solutions have been proposed to tackle this challenge, such as signal compression and sparse beamforming. However, in these schemes, the data transmitted in the fronthaul is proportional to the aggregated traffic of all TDs, and the fronthaul link capacity can still be a bottleneck in a very dense network.

On the other hand, if TR technology is used as the air interface in C-RAN, due to its unique spatial and temporal separation effects, all TDs are naturally separated by the location-specific signatures in both downlink and uplink, and the baseband signals for all TDs can be efficiently combined and transmitted. This unique feature of TR technology can be leveraged to create in essence a tunneling effect between the BBUs and the RRHs to alleviate the traffic load in the fronthaul link of C-RAN.

The data rate in the fronthaul connecting the BBUs and each RRH is only dependent on the system bandwidth and the number of bits used for every symbol, thus serving more TDs will not increase the traffic on the fronthaul link. Figure 11 shows the performance comparison in terms of normalized total transmitted data versus the number of TDs, where the normalization is performed over the transmitted data of the single TD case. The normalized total transmitted data in the fronthaul in an LTE-based C-RAN increases linearly with the number of TDs, while that of a TR-based C-RAN almost keeps constant, showing that the TR tunneling effect can deliver more information in the C-RAN and alleviate the burden of the fronthaul caused by network densification, a feature essential to next-generation systems.

Low complexity

Since TR systems essentially treat the rich-multipath environment as a computing machine that facilitates matched filtering, the receiver can perform a simple one-tap detection and thus the complexity of TR systems can be significantly reduced—essentially, the environment is doing the analog signal processing! As discussed in [16], by convolving the signal sequences with the TR signature waveforms, a TR system can concentrate most of the computational complexity at the more powerful AP-side while keeping the complexity of TDs at a minimal level, i.e., the TR system exhibits a unique asymmetric architecture. This desirable feature can provide less complexity and thus lower the cost of the TDs, which is ideal for supporting IoT [16].

Additional features

Besides the features previously discussed, there are many additional features when operating TR systems in a rich-scattering environment. For example, the unique spatial focusing effect can be used to significantly improve the resolution of indoor positioning systems [12]. The idea is to utilize the location-specific characteristic of multipaths. That is, for each physical geographical location, there is a unique logical location in the multipath space. By matching the multipath profile with those in the database, the physical location can be identified. Real-world experiments show that the TR-based indoor positioning system can achieve perfect 1–2 cm localization accuracy with a single AP working in the ISM band with bandwidth 125 MHz under the non-LOS condition [12].

Moreover, the unique location-specific multipath profile can be exploited to enhance the system security at the physical layer, where the user at the intended location can receive better SINR than all other ineligible users at different locations. Another interesting and unique feature is the pinpoint beamforming effect, i.e., the spatial focusing can be a 3-D "ball" by utilizing the distributed virtual antennas that naturally exist at different geographic locations.

Conclusions and discussions

We have shown the major features of TR, including massive multipath effect, energy efficiency, high capacity, scalability for network densification, tunneling effect for cloud-based networking, low complexity, and some additional features such as improving the resolution of indoor positioning systems and providing physical layer security. Such features collectively address the major challenges of 5G indoor communications. Therefore, TR appears to be a promising platform for 5G indoor and offer great opportunities for the community to develop further.

However, some challenges deserve more consideration in the future:

- *Number of multipaths*: The performance of TR systems depends highly on the degrees of freedom in the environment, i.e., the number of multipaths. The larger the number of multipaths, the higher the TR focusing gain and thus the better the performance. When the number of multipaths varies from place to place, one may want to ensure the same performance.
- *Dynamic environment*: One implicit assumption of TR systems is that the channel is stationary. In a dynamic environment, the estimated channel in the channel probing phase may not be consistent with the real channel in the data transmission phase, due to which the focusing gain may be reduced causing performance degradation. Through real experiments, one can see that the channel is quite stable as long as there is no severe disturbance of the environment [9], [12]. When the environment is highly dynamic, one may need to probe the channel more frequently to sustain the operation.
- *Mobility*: The benefit from the focusing effect of TR relies on accurate channel estimation. If the transmitter and/or receiver become mobile, the channels are no longer reciprocal when the speed is faster than what the channel coherent time can handle, and the focusing gain may drop greatly due to outdated channel estimate. Therefore, the channel needs to be reprobed in mobile TR systems, and the reprobing will be more challenging if there are many TDs or the TDs are moving at a high speed.
- *Synchronization/timing*: Finding the right timing of the focusing peak is critical to facilitate the TR system operation. This can be resolved through oversampling and performing synchronization in the oversampled domain, which, however, will increase the cost of analog-to-digital converters and digital-to-analog converters.

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