TIME REVERSAL FOR 6G SPATIOTEMPORAL FOCUSING

Recent Experiments, Opportunities, and Challenges

George C. Alexandropoulos, Ali Mokh, Ramin Khayatzadeh, Julien de Rosny, Mohamed Kamoun, Abdelwaheb Ouirir, Arnaud Tourin, Mathias Fink, and Mérouane Debbah

Late visions and trends for the future 6G of wireless communications advocate, among other technologies, the deployment of network nodes with extreme numbers of antennas and up to terahertz frequencies as a means to enable various immersive applications. However, these technologies impose several challenges in the design of radio-frequency (RF) front ends and beamforming architectures as well as ultrawideband waveforms and computationally efficient transceiver signal processing. In this article, we revisit the time-reversal (TR) technique, which was initially experimented in acoustics, in the context of large-bandwidth 6G wireless communications, capitalizing on its high-resolution spatio-temporal focusing realized with low-complexity transceivers. We first overview the representative state of the art in TR-based wireless communications, identifying the key competencies and requirements of TR for efficient operation. Recent and novel experimental setups and results for the spatiotemporal-focusing capability of TR at the carrier frequencies 2.5, 36, and 273 GHz are then presented, demonstrating in quantitative ways the technique’s effectiveness in these very different frequency bands as well as the roles of the available bandwidth and the number of transmit antennas. We also showcase the TR potential for realizing low-complexity multiuser communications. The opportunities arising from TR-based wireless communications as well as the challenges for finding their place in 6G networks, also in conjunction with other complementary candidate technologies, are highlighted.

The Article’s Motivation and Contribution

While the major telecommunications operators are currently deploying 5G wireless networks [1] in various
Radio communications based on TR exploit rich multipath propagation to offer high-resolution wave focusing in both space and time.

In this article, motivated by the large bandwidths available at mmWave and, most significantly, at the upcoming terahertz wireless communications, the respective necessity for simple transceiver signal processing and relevant hardware, and the recent advances with reconfigurable metamaterials for enabling programmable EM wave propagation control [13], we present novel experimental results showcasing the high-resolution spatiotemporal-focusing capability of the TR technique in a wide range of carrier frequencies with very different signal propagation characteristics. Believing that this significant property, which is realized via basic transceiver operations, can contribute to 6G wireless communications in terms of coverage extension, sensing, and localization, we investigate the key requirements for TR efficient operation and demonstrate the role of the available bandwidth and the number of transmit antennas on its performance. We discuss applications and opportunities with TR-based wireless communications and highlight their open challenges and research directions in conjunction with complementary technologies.

The TR Principle in Wireless Communications

According to the TR framework, radio waves can be focused onto the location of a user terminal by emitting a time-reversed version of the user’s transmitted signal. For example, let us assume a single-antenna user emitting, in the uplink, a transient wave (e.g., a chirp signal) that propagates inside a complex wireless medium that can be inhomogeneous, scattering, or reverberating [6]. The time dependence of the emitted field’s components can be probed by a single- or multiantenna base station and then downconverted to baseband. Afterward, this resulting digital signal can be time reversed and upconverted to the analog domain for transmission in the downlink direction. Because of the reciprocity principle in TDD wireless communications, the latter downlink transmitted wave will have the same impulse response as its uplink counterpart, and it will become focused on the user position. This capability was first exploited for underwater wireless communications with acoustic signals [5] and later considered and tested for 5G and beyond single- and multiuser wireless communications [7], [10].

The efficient application of TR requires, in principle, rich scattering environments that enable multipath wave propagation as well as large transmission/communication...
Vivaldi antenna was generated by the AWG and with variable...

MIMO [native technology to OFDM with and without massive...

As well as very recently in indoor user localization...

For large-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.

For larg-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.

For larg-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.

For larg-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.

For larg-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.

For larg-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.

For larg-bandwidth communications, such as those at mmWave and the envisioned terahertz frequencies in 6G, the implementation of OFDM will require increased computational complexity since significantly increased numbers of subcarriers will be utilized. However, with TR, the ultrawideband channels can be estimated using an easily generated chirp signal (e.g., transmitted from the intended user in the uplink), and the TR-based precoding using the conjugate frequency response for each subcarrier can be applied, which is again equivalent to performing TR precoding in the time domain. It is noted that MRT requires channel estimation via pilot signals for all subcarriers (this is a computationally demanding process), whereas TR is based on the CIR recording/estimation, which can be, in general, simpler.
mmWave Setup
The realized mmWave setup at the central frequency $f_c = 36$ GHz with bandwidth $B = 2$ GHz deploys a 30 cm $\times$ 20 cm $\times$ 20 cm closed metallic box, as depicted in Figure 1(b), that includes multiple closely placed vertical rods to enable multiple reflections of the transmitted signal. As shown in the figure, the side of the box that faces the Rx antenna has a square window of width $d = 5$ cm, while a similar Tx antenna is placed on another side of the box that is perpendicular to the window. We have used A-INFO octave horn antennas for both the Tx and Rx, with wideband operation from 18 to 40 GHz with a 20-dB gain. The orientation of the Tx antenna is such that the emitted waveform faces the rods before reaching the window and, consequently, the Rx antenna. The latter antenna is placed on a motorized axis at a distance $D = 20$ cm from the box, enabling its parallel movement to the box’s window. We considered that the point $x = 0$ on the axis, where the Rx antenna lies, faces the center of the metallic box.

Instead of using an AWG and a DSO in our designed mmWave experiment, as we did for the sub-6-GHz one, we deployed an R&S ZNA43 vector network analyzer (VNA) to sound, in the frequency domain, the channel between the Tx and Rx antennas. This channel sounding was performed, as previously mentioned, around 36 GHz with 2 GHz of bandwidth. To emulate the TR processing, we first numerically transformed the channel’s frequency response, which was probed by the VNA, to the CIR using a discrete Fourier transform and then flipped it in the time domain. Finally, this time-domain signal was convoluted with all probed CIRs.

Sub-THz Setup
Our experimental setup at $f_c = 273.6$ GHz using a 5 cm $\times$ 5 cm $\times$ 5 cm closed metallic box is demonstrated in Figure 1(c). Similar to the mmWave case, to create the rich multipath needed for efficient TR operation, we have created a small window on one side of the box, with its perpendicular side opened and replaced with a metallic square plate having multiple small holes of diameter less than 1 mm. Both the Tx and Rx are equipped with identical WR-2.8 horn antennas (operating from 260 GHz up to 400 GHz), the former facing the small window, and the latter placed on a motorized axis, as shown in Figure 1(c). The axis of the Rx antenna movement is parallel to the plate and, consequently, to one side of the box, with a separating distance $D = 5$ cm. As shown in the figure, the point $x = 0$ on the axis faces the center of the metallic box.

To create transmitted signals in the sub-THz domain, we generated a reference sinusoidal signal at the desired frequency $f_c = 273.6$ GHz as follows. The deployed R&S SGMA local oscillator produced a sinusoid at 5.7 GHz, which was then upconverted for transmission using a WR2.2 VDI SAX WM570 harmonic mixer (operating at 260 GHz up to 400 GHz with a transmit power of $\pm 10$ dBm) whose multiplication factor was set to 48 (note

![Figure 1](image-url)
that $5.7 \times 48 = 273.6$). At the Rx side, a harmonic mixer with the same multiplication factor was deployed for downconversion back to 5.7 GHz. Both the AWG to generate the baseband signal of bandwidth 3 GHz and the acquisition card to detect it were connected to the same clock reference working at 10 MHz. The CIR estimation was performed similarly as in the sub-6-GHz experiment, and TR precoding was simulated in the desktop computer similarly as in the mmWave experiment.

**Results for Sub-6-GHz Setup**

The impact of the number of transmit antennas $N_t$ and the communication bandwidth $B$ in the spatiotemporal-focusing capability of TR precoding, as implemented in the experimental setup of Figure 1(a), was thoroughly investigated, and representative results are illustrated in Figure 2. In particular, we first emulated a TR-processed CIR of power $-4$ dBm with bandwidth values $B = (100, 200, 400)$ MHz to focus toward the position $x = 10$ cm and measured the baseband received signal strength at 30 distinct Rx positions, ranging from the point $x = 0$ cm in the motorized axis to $x = 30$ cm, with a space separation of 1 cm. When $B = 100$ MHz was considered for $N_t = 1$ (a single-input, single-output system) and for two multiple-input, single-output (MISO) configurations for $N_t = 2$ and 8, the received signal strength indeed took its maximum value around $x = 10$ cm, while it was shown that this value increases with increasing $N_t$. More specifically, for the $8 \times 1$ MISO wireless system that yielded the best TR-based spatiotemporal-focusing capability, it was corroborated that the received signal strength gets its maximum value around the intended Rx position with a spatial resolution of 6 cm and in 10-ns temporal resolution. It is noted that the resulting spatial width of the signal-focusing area is approximately equal to half of the signal wavelength; recall that $f_c = 2.5$ GHz.

The potential of TR precoding to create less interference in unintended Rx positions, thanks to its spatiotemporal-focusing efficiency, and the role of the bandwidth $B$ on its time-focusing capability are demonstrated in Figure 2 for the considered $8 \times 1$ MISO wireless system. As depicted in Figure 2(a) for $B = 100$ MHz, a spatial resolution of 6 cm is sufficient to focus the transmitted signal simultaneously toward the two different positions at $x = 7.5$ cm and $x = 20$ cm. Considering the position $x = 10$ cm and $B = 400$ MHz, Figure 2(b) showcases that increasing $B$ results in improved temporal focusing of the received signal. It is particularly depicted in Figure 2(b) that the time resolution of the received signal is approximately equal to 2.5 ns, while for $B = 100$ and 200 MHz the resolution was 10 and 5 ns, respectively. In conclusion, our experimental results prove that the TR-based time resolution is approximately equal to the inverse of the signal bandwidth.

**Results for mmWave Setup**

The capability of TR to spatiotemporally separate the two Rx positions at $x = -1$ cm and $x = 1$ cm is illustrated in Figure 3. In particular, the amplitudes in volts of the CIR components when TR is applied at either of the two positions are depicted. It is evident that, by applying TR, we are able to focus two different signals toward the two intended Rx positions. In Figure 3(a) and (b), when targeting a specific position, a focusing signal at the time instant $t = 0$ is significantly higher than the level of interference (interuser and intersymbol interference), which implies that space multiplexing can be achieved, thanks to TR in this frequency range. This means that, with TR, we can send two different data streams toward two different Rx positions separated by 2 cm. This has been termed in past theoretical works as the TR division multiple access (TRDMA) scheme [10].

**Results for Sub-THz Setup**

In Figure 4, the TR spatiotemporal-focusing capability with the sub-THz experimental setup of Figure 1(c) is illustrated. We transmitted a signal of power $-10$ dBm covering a bandwidth $B = 3$ GHz and measured the received signal strength at 21 distinct positions of the Rx antenna in the motorized axis, ranging from the point $x = -3$ mm to $x = 3$ mm, with a space resolution of 0.3 mm. As shown in Figure 4(b) and (c), the width of the TR spatial-focusing capability (i.e., the yellow colored area) in both considered time-orthogonal true Rx positions is approximately equal to the signal wavelength, which is 1 mm, and the temporal resolution is less than 1 ns. Figure 4(a) also

![Figure 2](image-url)
depicts for the designed experimental setup that no spatiotemporal focusing at the intended Rx positions is feasible when TR processing is not applied.

Opportunities and Open Challenges
The experimental results of the previous section for three carrier frequencies with very different signal propagation characteristics and large, but reasonably large for beyond 5G, transmission bandwidths showcased that TR can offer signal spatial focusing approximately equal to the wavelength with a temporal resolution of the order of the inverse of the transmission bandwidth, i.e., of a few nanoseconds. In this section, we discuss representative opportunities for future wireless communications resulting from TR's capabilities, while identifying key open challenges for TR to be a strong candidate technology for 6G wireless communications.

Opportunities
As discussed in the section “TR for Wireless Communications,” the TR technique requires the estimation of the CIR, which can be realized with simple signal processing from the Tx that generates the information data. Then the Rx can deploy a simple reception module for information decoding. To this end, in TDD communications, the CIR can be estimated in a dedicated uplink phase followed by the TR-precoded information transmission in the downlink. We next present some of the key opportunities with TR.

Inherent Localization and Sensing
The high-resolution spatiotemporal-focusing capability of the TR technique, as showcased in all experimental results in the section “TR for Wireless Communications” and in the recent laboratory experiments in [11], can be naturally exploited for localization and sensing. The latter two applications are currently highly relevant for 6G wireless communications [4], as both end services as well as prerequisites for several high-performance applications (e.g., immersive and vehicular communications and integrated communications and radar). As has been demonstrated in the available results for indoor environments, TR precoding offers signal focusing at an intended Rx position with centimeter-level accuracy. This feature enables highly localized signal delivery,

Figure 3 The amplitudes in volts of the CIR components for the mmWave system in Figure 1(b) operating at 36 GHz with bandwidth \( B = 2 \) GHz and considering two Rx positions at the points \( x = –1 \) cm and \( x = 1 \) cm. TR is applied and the received signal is shown for (a) \( x = –1 \) cm and (b) \( x = 1 \) cm.

Figure 4 The TR spatiotemporal-focusing capability of the subTHz system in Figure 1(c) operating at 273.6 GHz with bandwidth \( B = 3 \) GHz for different Rx positions. (a) The received signal strength without applying TR. (b) \( x = –1.8 \) mm. (c) \( x = 1.2 \) mm.
increasing signal coverage and reducing signal leakage (i.e., interference) at nearby Rx positions. The CIR estimation, which is the initial phase of the TR technique, can also be incorporated with machine learning techniques to map the CIR referring to an intended Rx position to absolute location estimation. Hence, TR can be considered either alone or synergistically with other superresolution approaches for high-precision positioning systems.

High-resolution imaging, which encompasses the family of approaches for sensing cooperating active users in a given wireless environment surveilled by a plurality of transceivers, has also relied on variants of the TR technique. Combined with superresolution signal classification techniques, TR has been applied for environmental imaging of point targets from arbitrary sensor array geometries, with applications in seismoacoustics and ocean acoustics and in ultrasonic nondestructive evaluation systems. This TR-enabled feature can be exploited for designing radio cartography maps that can be used for spatiotemporal resource allocation optimization and service provisioning.

Low-Complexity Reception
In contrast to OFDM, which requires an increased computational complexity that increases significantly with the number of subcarriers, TR relies on time-domain channel estimation (i.e., CIR estimation), using, for example, chirp signals, and enables simple, even single-tap, reception. This fact can motivate the adoption of low-complexity TR-based receivers for user equipment in large-bandwidth wireless communications, such as those in mmWave frequencies and for the provisioned terahertz bands in 6G. In addition, TR can be further combined with spatial modulation for facilitating low-complexity reception for single-carrier wireless communications, enabling noncoherent signal detection (e.g., via ON/OFF keying or pulse-position modulation) at battery-limited and computationally basic devices intended for the Internet of Things (IoT). For example, in a recent work [15], TR was successfully deployed for receive spatial modulation, where IoT devices were equipped with one reconfigurable antenna and a noncoherent signal detector.

Multiuser Transmissions
The interpretation of the CIR results in Figure 3 corroborated the potential of TR for multiuser spatial multiplexing. It was specifically advocated that TR can be used to concurrently transmit two different data streams toward two centimeter-separated Rx positions. There has also been increased interest in the relevant literature for efficient signal processing techniques to reduce the effect of the unavoidable interference caused by conventional TR precoding. To this end, an iterative TR process requiring feedback between the Tx and a given Rx has been introduced, according to which the interference is iteratively subtracted at that Rx using a precoded TR signal. The concept of TRDMA [10] also has been theoretically shown to provide a cost-effective waveform for multiple accessing of energy-efficient IoT nodes. Hence, TR offers various perspectives for large numbers of simultaneous transmissions intended for multiple low-complexity receivers.

Research Challenges
The designed experimental setups for TR in Figure 1 include either a reverberating cavity or metallic boxes that mechanically create strong multipath signal propagation. Similar rich scattering conditions were created for the laboratory experiments in [11], where it was found that, for channels centered at 3.5 GHz with at least 10 strong multipath components and more than a 100-MHz channel sounding capability, TR-based precoding provides less than 5-cm spatiotemporal focusing and up to 4-dB signal coverage improvement. Given the requirements for efficient TR operation, we next discuss some of the key challenges with TR and its emerging applications:

EM Wave Propagation Control
The efficacy of TR highly depends on the diversity in signal propagation paths in time. The higher the number of paths, the better the TR performance. In fact, for scenarios with poor multipath performance, TR is usually inefficient. This means that TR should be applied only in physically or artificially customized rich scattering scenarios. For the latter case, intelligent reflecting metasurfaces [13] can be deployed close to either the Tx or Rx, or both, or can even be a part of each of them (depending on the carrier frequency), whose operation needs to be jointly optimized with TR precoding. To this end, the interplay between multipath richness and TR efficiency needs to be fully characterized to be dynamically manipulated via low-overhead algorithms by reconfigurable metasurfaces.

Interference Management
As depicted in Figure 3, TR focuses the signal in time and space by maximizing the central peak at the intended Rx position. However, this approach does not annihilate interference either in time or in space, possibly resulting in intersymbol and interuser interference that can limit
the performance of TR-based multiuser wireless communication systems. This problem is more severe when spatially correlated signal propagation paths exist among the plurality of the users. To alleviate such interference problems, efficient interference-handling techniques for TR need to be designed.

Mobility and Synchronization

The TR technique relies on the reciprocity property of wireless communication channels. If the Tx and/or the Rx is mobile, the received signal level varies with the node’s speed. If that speed is higher than what the channel coherence time can handle, the CIR estimation could be outdated, resulting in spatiotemporal focusing for an erroneous Rx position. Hence, efficient synchronization methods are necessary for TR-linked nodes that dynamically capture the spatiotemporal coherence of the wireless channel.

Fragmented Large Bandwidth

As previously discussed, the availability of large communication bandwidths enables high-resolution CIR estimation, which is essential for TR. However, in sub-6-GHz applications, large communication bandwidths are either infeasible or can be available only via carrier aggregation. It is appealing to investigate the design of TR techniques for large-bandwidth communications resulting from the aggregation of fragmented bandwidth chunks.

Synergies With Other Technologies

Despite the promising experimental results with TR, advances in algorithmic design and experimentation for TR-precoded data communication considering single-user multistream MIMO and multiuser massive MIMO systems are required. In addition, the adequate regimes and applications of TR need to be fully characterized in conjunction with the technique’s promising synergies with other candidate 6G technologies, like holographic MIMO and orbital angular momentum, which exhibit the potential for enabling service delivery with high spatiotemporal resolution and multiuser multiplexing. Finally, the interplay of TR with physical-layer security necessitates investigation to unveil the TR potential for CIR-based information encryption.

Conclusions

In this article, inspired by the current trends in mmWave and terahertz technologies as well as in localization and sensing for beyond-5G networks, we have experimentally investigated the spatiotemporal-focusing capability of the TR technique in large-bandwidth wireless communications with various carrier frequencies, ranging from sub-6-GHz to sub-THz domains. We discussed the underlying principle of TR with some representative demonstrations and considerations to date and presented its key competencies in terms of low-complexity transceiver hardware and signal processing as well as its requirements for rich scattering and large communication bandwidths. Our experimental results showcased the roles of the frequency band and its width and also the number of transmit antennas in TR spatiotemporal focusing in a single and multiple spots. Indicatively, it was demonstrated for the first time in the sub-THz domain that TR is capable of offering spatial focusing of less than 1 mm and less than 1-ns temporal resolution with a 3-GHz bandwidth. We finally highlighted the opportunities and challenges arising from TR in 6G wireless communications and discussed its promising synergies with other emerging technologies.

Author Information

George C. Alexandropoulos (alexandg@di.uoa.gr) is an assistant professor with the Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Athens 15784, Greece. He also is a principal researcher at the Technology Innovation Institute, Abu Dhabi, United Arab Emirates. His research interests include algorithmic design and performance analysis for wireless networks, emphasizing on multiantenna transceiver hardware architectures, reconfigurable metasurfaces, millimeter-wave and terahertz communications, and distributed machine learning. He is a Senior Member of IEEE.

Ali Mokh (ali.mokh@espci.fr) is a postdoctoral researcher at ESPCI Paris, PSL Research University, National Centre for Scientific Research, Institut Langevin, Paris 75005, France. He received his Ph.D. degree in digital communications from INSA de Rennes, France, in 2018. His current research interests include time-reversal precoding for multiple-input, multiple-output communications in sub-6-GHz, millimeter-wave, and subterahertz systems. He is a Member of IEEE.

Ramin Khayatsadeh (ramin.khayatza.deh1@huawei.com) is a senior researcher at Mathematical and Algorithmic Sciences Lab, Paris Research Center, Huawei Technologies France, Boulogne-Billancourt 92100, France, working on beyond 5G technologies. He received his Ph.D. degree at IMEP-LAHC Laboratory, National Polytechnics Institute of Grenoble,
France, in 2016. His main research interests are terahertz communication systems and radio-over-fiber, microwave photonic, and sensing technologies.

**Julien de Rosny** (julien.derosny@espci.fr) is a senior scientist at ESPCI Paris-PSL Research University, National Centre for Scientific Research, Institut Langevin, Paris 75005, France. During the 2000–2001 academic year, he was a postdoctoral fellow in the Marine Physical Laboratory at Scripps Research Institute, La Jolla, CA, USA. His fields of interest include propagation and time reversal of acoustic and electromagnetic waves in complex media applied to imaging and telecommunications.

**Mohamed Kamoun** (mohamed.kamoun@huawei.com) is a principle engineer with the Mathematical and Algorithmic Sciences Lab, Huawei Paris Research Center, Boulogne-Billancourt 92100, France. He received his engineering degree from ENSTA Paris-Tech in 2001 and his Ph.D. degree from the Université Paris-Sud in 2006. His research interests include PHY layer and channel modeling for 6G communications, algorithm design for digitally controllable scattering, and for joint communication and sensing in wireless systems. He is a Member of IEEE.

**Abdelwaheb Ourir** (a.ourir@espci.fr) has been a research engineer at ESPCI Paris, PSL Research University, National Centre for Scientific Research, Institut Langevin, Paris 75005, France, since 2008. He received his engineering degree from the École Nationale d’Ingénieurs de Tunis, Tunisia, in 2003 and his Ph.D. Degree in physics from Paris-Sud University, Paris, France, in 2007. His current research interests include metamaterial-based antennas, electromagnetic subwavelength imaging, guided waves, and wave propagation in artificial materials.

**Arnaud Tourin** (arnaud.tourin@espci.psl.eu) is a professor at ESPCI Paris, PSL Research University, National Centre for Scientific Research, Institut Langevin, Paris 75005, France; he is the head of Institute Langevin. He received his Ph.D. degree in physical acoustics from the University of Paris, France, in 1999. His research interests include time reversal applied to wireless communications and geophysics and wave propagation in strongly scattering media.

**Mathias Fink** (mathias.fink@espci.fr) is the George Charpak Professor at ESPCI Paris, PSL Research University, National Centre for Scientific Research, Institut Langevin, Paris 75005, France, where in 1990 he founded the Laboratory “Ondes et Acoustique,” which became the Langevin Institute in 2009. His current research interests include wave control in complex media, time reversal in physics, metamaterials, superresolution, wireless communications, medical ultrasonic imaging, and multiwave imaging.

**Mérouane Debbah** (merouane.debbah@tti.ae) is chief research officer at the Technology Innovation Institute and is also with Mohamed Bin Zayed University of Artificial Intelligence, Masdar City, Abu Dhabi 9639, United Arab Emirates. He received his degree from the École Normale Supérieure Paris-Saclay, France. In 2014–2021, he was vice president of the Huawei Technologies France Research Center. His research interests include fundamental mathematics, algorithms, statistics, information, and communication sciences research. He is a Fellow of IEEE.

---

**References**

[1] M. Shafi et al., “5G: A tutorial overview of standards, trials, challenges, deployment, and practice,” IEEE J. Sel. Areas Commun., vol. 35, no. 6, pp. 1201–1221, Jun. 2017, doi: 10.1109/JSAC.2017.2692307.

[2] “3GPP releases 16 & 17 & beyond,” 5G Americas, Bellevue, WA, USA, White Paper, Jan. 2021. [Online]. Available: https://www.5gamericas.org/3gpp-releases-16-17-beyond.

[3] “The next hyper-Connected experience for all,” Samsung 6G Vision, Suwon-si, South Korea, White Paper, Jun. 2020. [Online]. Available: https://cdn.codeground.org/nts/downloads/researchareas/6G%20Vision.pdf

[4] W. Saad, M. Bennis, and M. Chen, “A vision of 6G wireless systems: Applications, trends, technologies, and open research problems,” IEEE Netw., vol. 34, no. 3, pp. 1–9, Oct. 2019, doi: 10.1109/MNET.001.1900287.

[5] M. Fink, “Time reversal of ultrasonic fields, Part I: Basic principles,” IEEE Trans. Ultrason., Ferroelect., Freq. Control, vol. 39, no. 5, pp. 555–566, Sep. 1992, doi: 10.1109/58.156174.

[6] G. Lerosey, J. de Rosny, A. Tourin, A. Derode, G. Montaldo, and M. Fink, “Time reversal of electromagnetic waves,” Phys. Rev. Lett., vol. 92, no. 19, pp. 1–3, 2004, doi: 10.1103/PhysRevLett.92.193904.

[7] Y. Chen, B. Wang, Y. Han, H.-Q. Lai, Z. Salar, and K. J. R. Liu, “Why time reversal for future 5G wireless?” IEEE Signal Process. Mag., vol. 33, no. 2, pp. 17–26, Mar. 2016, doi: 10.1109/MSP.2015.2506347.

[8] Y. Song, N. Guo, and R. C. Qiu, “Implementation of UWB MIMO time-reversal radio testbed,” IEEE Antennas Wireless Propag. Lett., vol. 10, pp. 796–799, 2011, doi: 10.1109/LAWP.2011.2162717.

[9] R. C. Qiu, J. Q. Zhang, and N. Guo, “Detection of physics-based ultra-wideband signals using generalized RAKE with multiuser detection (MUD) and time-reversal mirror,” IEEE J. Sel. Areas Commun., vol. 24, no. 4, pp. 724–730, Apr. 2006, doi: 10.1109/JSAC.2005.863813.

[10] F. Han, Y.-H. Yang, B. Wang, Y. Wu, and K. J. R. Liu, “Time-reversal division multiple access over multi-path channels,” IEEE J. Sel. Areas Commun., vol. 60, no. 7, pp. 1953–1965, Jul. 2012, doi: 10.1109/TCOMM.2012.051012.110531.

[11] G. C. Alexandropoulos, R. Khayatadeh, M. Kamoun, Y. Ganghua, and M. Debbah, “Indoor time reversal wireless communication: Experimental results for localization and signal coverage,” in Proc. IEEE Int. Conf. Acoust., Speech Signal Process., Brighton, U.K., May 12–17, 2019, pp. 7844–7848, doi: 10.1109/ICASSP.2019.8683188.

[12] X. C. Jiang, Y. Han, B. Wang, and K. R. Liu, “Waveforming: An overview with beamforming,” IEEE Commun. Surveys Tuts., vol. 20, no. 1, pp. 132–149, 2018, doi: 10.1109/COMST.2017.2750201.

[13] P. del Hougne, M. Fink, and G. Lerosey, “Optimally diverse communication channels in disordered environments with tuned randomness,” Nature Electron., vol. 2, no. 1, pp. 36–41, Jan. 2019, doi: 10.1038/s41928-018-0190-1.

[14] A. Mokh, Y. Kokar, M. Hêlard, and M. Crussiere, “Time reversal receive antenna switch keying on MIMO LOS channel,” in Proc. IEEE Sensors Netw. Smart Emerg. Technol., Beirut, Lebanon, Sep. 2017, pp. 1–4, doi: 10.1109/SENSNET.2017.8125068.

[15] D.-T. Phan-Huy et al., “Single-carrier spatial modulation for the Internet of Things: Design and performance evaluation by using real compact and reconfigurable antennas,” IEEE Access, vol. 7, pp. 18,978–18,993, 2019, doi: 10.1109/ACCESS.2019.2985754.