# Physicists in a World of Wireless Communications: A Noisy Connection?

Geoffroy Lerosey and Mathias Fink

About 15 years ago, coming from the world of wave physics in complex media, we wanted to change the way wireless communications worked by introducing smart beamforming techniques relying on a large array of transceivers. These ideas, based on the concept of time reversal, received extremely skeptical feedback from the wireless communications community, which considered them too complicated to implement. What a surprise it was when, 10 years later, a major telecommunication operator we had been in contact with performed a live demonstration of our approach at the Mobile World Congress! The story starts over again with the concept of reconfigurable intelligent surfaces (RISs). Inspired by work we had done in optics, we proposed to use reconfigurable metasurfaces as smart walls for enhanced and greener wireless communications. The proposal again received an ultracold welcome from the experts. We are extremely happy to see the excitement around it now, with publicly-funded projects, thousands of publications, some IEEE work groups, and even standardization efforts. Yet this puzzles us, and we want to ask if there is a good enough connection between physics and wireless communications?

## EDITOR'S NOTE


Rod Waterhouse

Welcome to this edition of the "Industry Activities" column. This month, we have the pleasure reading a contribution authored by Geoffroy Lerosey and Mathias Fink, which provides interesting insight into the challenges of starting a company based on ideas that are not considered "mainstream" in terms of conventional wireless engineering. One of the great lessons for any engineer is to be open minded: a concept is not wrong simply because it is difficult to understand. I am sure we have all had trouble with this during discussions with researchers and engineers who have different backgrounds and training. However cross-disciplinary ideas are extremely important for technology advancement.

## TIME REVERSAL AND MASSIVE MULTIPLE-INPUT, MULTIPLE-OUTPUT

Ultrasonics have been for years a playground for wave physicists for two main reasons. On the one hand, the typical frequencies of conventional ultrasounds, which lie in the megahertz, make them extremely friendly waves for physicists. Indeed, the electronics that are necessary to generate and acquire them are relatively simple, and they enable practical, small-scale experiments due to their typical millimeter-size wavelength in water. On the other hand, since they can be used to image inside the human body in ultrasonography, tremendous efforts were made in the second half of the 20th century to develop fully programable arrays of transceivers.

So, this is how it all started, in the field of ultrasounds, at the beginning of the 1990s. If free-space beamforming methods were well known and used in ultrasound imaging, complex media were still viewed as a nightmare. Yet, considering that wave equations are reversible in time, Mathias Fink proposed the concept of time reversal [1], [2]. The idea consists of recording and digitizing time-dependent impulse responses between a source and an array of transceivers after propagation through any medium, flipping them in time, and emitting the newly fabricated time-reversed signals. Due to the reciprocity and reversibility of wave equations, waves focus back on the source, whatever the complexity of the propagation medium. Time reversal was first demonstrated in the early 1990s for broadband signals [3], where

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the authors proved that ultrasounds can be focused onto very sharp spatiotemporal spots even after propagating through multiple scattering media, such as thick forests of steel rods in water (see Figure 1).

A few years later, we showed that this approach could be used to communicate with large arrays of sources by harnessing spatial multiplexing, mitigating multipath time spreading, and increasing the bandwidth efficiency and energy efficiency of the systems [4]–[6]. This was initially realized through a multiple scattering medium and then in a small-scale setup mimicking a city in a water tank. So, while most research in the field of wireless communications was limited to theoretical works or discovering only that scattering could help rather than deteriorate wireless communications [7]–[10], works on ultrasound were pioneering the first experimental proofs of the massive multiple-input, multiple output (MIMO) concept and even making a link with the capacity of propagation media [5], [6], [11]. We later expanded these works to the microwave domain (Figure 2) by demonstrating time reversal across a carrying frequency, which, in the case of very narrow bandwidths, amounts to phase conjugation [12], [13]. We essentially proved that the benefits of time reversal for wireless communications were observed in ultrasound: temporal compression of time-spread signals, spatial multiplexing, and energy efficiency.

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As physicists, we had tremendous problems discussing these ideas with researchers from the wireless communications community, and trying to publish in their journals was a nightmare. After several tries, we ended up publishing our work in physics-oriented journals. Meanwhile, we created a startup company, Time Reversal Communications, aimed at pushing these ideas toward the market. With the company's team, we toured every actor in the field, starting with telcos then going to hardware manufacturers, integrators, service providers, and so on. We did this within many markets, from large cellular to Wi-Fi, then to Worldwide Interoperability for Microwave Access and even ultrawideband. Every time the answer was similar: the technology was too complex, acquiring the channel knowledge at the transmitter would be too time consuming, and the benefit was unclear compared to known MIMO techniques (which, by the way, never went further than maximum ratio combining, due to algorithm complexity). Long story short, the company never took off and finished its rather poor life in the pocket of a large corporation, for reasons that are far from fostering innovation.

It is interesting, in light of this story, to consider how things have changed within approximately 15 years. Forgetting about the marketing moves discussed previously, the time seems to have come for these ideas, as massive MIMO is being deployed for 5G. Of course, it is not exactly the version we proposed years ago, and, had we dug seriously into more technological considerations, we would have seen what seemed scary in our proposal. Most importantly, all wireless systems now have left the time domain for the much

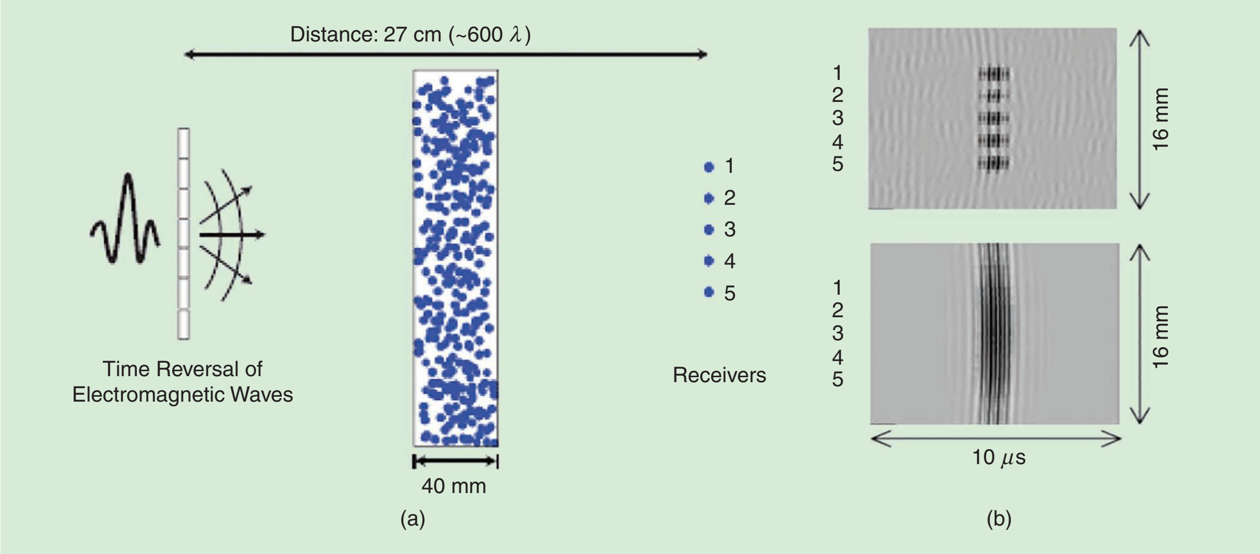


**FIGURE 1.** Ultrasonic time reversal focusing is used to concentrate waves spatiotemporally onto five foci from an array of 23 antennas. (a) The result obtained in the presence of a multiply scattering medium. Since the scattering medium acts like a focusing lens of great angular aperture, each focal spot is much thinner, and five independent beams are created, enabling spatial multiplexing with independent and closely spaced spots. (b) The result obtained in free space: no more spatial multiplexing is possible in this configuration.

more robust orthogonal frequency-division multiplexing scheme, and proposing a technology based on time-controlled signals and high-speed analog-to-digital converters/digital-to-analog converters was not clever. Yet, this is just a matter of the Fourier transform, and there is a lot to bet on the fact that the technology being installed is strongly linked to the proposal we made. And this raises the question of the penetration of ideas from physics into wireless communications and, more generally, the pace of innovation in the field. Still, on our side, we decided to move forward, convinced that we had proposed something much too complex, looking to simplify to the extreme our ideas of wave control. At that time, we were doing optics …

## WAVEFRONT SHAPING AND RISs

Among the people who followed our work, many were researchers from the optical community, and almost all of them were jealous of the tremendous things ultrasound enabled us to do with waves. Indeed, if radio-frequency signals are much higher in frequency than ultrasound, think about light. People in the optics community have no means to digitize and generate time-dependent signals at the typical frequencies of light, and playing tricks with waves as we did, for instance, time reversal, was just a dream for them. This was the case until the birth of spatial light modulators (SLMs), about 20 years ago, which opened new possibilities to control narrow-band light, such as monochromatic laser beams. SLMs are matrices of pixels (from hundreds to millions) that can be either movable mirrors or liquid crystal unit cells. Each of these pixels, when activated with a current/potential, can modify the way light reflects off it. For instance, in digital micromirror devices (DMDs) that are commonly used in video projectors, each pixel can reflect light or not, resulting in binary amplitude modulation. The pixels of liquid crystal-based SLMs, on the contrary, can impose a controllable phase shift to light they reflect, with minimal amplitude distortion. Addressing all the pixels of an SLM at once enables totally controlling a wavefront of incoming light, in amplitude or phase or both if more complex setups are realized. A noticeable difference compared to time reversal is that the control is identical for each frequency component of the incident light wavefront.

As for beamforming techniques, the free-space use of SLMs had been well known for decades since it is at the basis of modern video projectors. The idea is to reflect a light source off a controlled DMD to project an image through a lens onto a wall. What physicists (among them, Allard Mosk, a pioneer in The Netherlands) brought is that SLMs can be used to control light very precisely even after propagation through scattering and complex media, hence initiating the field of wavefront shaping in optics. As a first experiment [14], Mosk and his team used a liquid crystal-based SLM and laser to shape light so that it focused into a sharp spot after propagating through a thick layer of white paint. Before shaping, the light exiting the layer of paint took the logical form of a speckle pattern, that is, a random distribution of low energy spreading on a broad area. But amazingly, after shaping, the light converged toward a very thin focal spot [see Figure 3(a)], providing a 1,000-fold intensity increase, analogous to what had been demonstrated 10 years before in the field of ultrasound by using time reversal [15].

To us, when this paper came out, it was a real paradigm change; indeed, we were specialists of wave control, accustomed to focusing and taming waves at will in any medium, whatever its complexity, but, notably for microwaves, we were using costly, bulky, and complex arrays of sources. These researchers had realized that it is much easier to control Huygens secondary sources through controlled reflections rather than actual sources via SLMs. From 2008 onward, we began to work in the field of optics with our colleagues and demonstrated many interesting things,

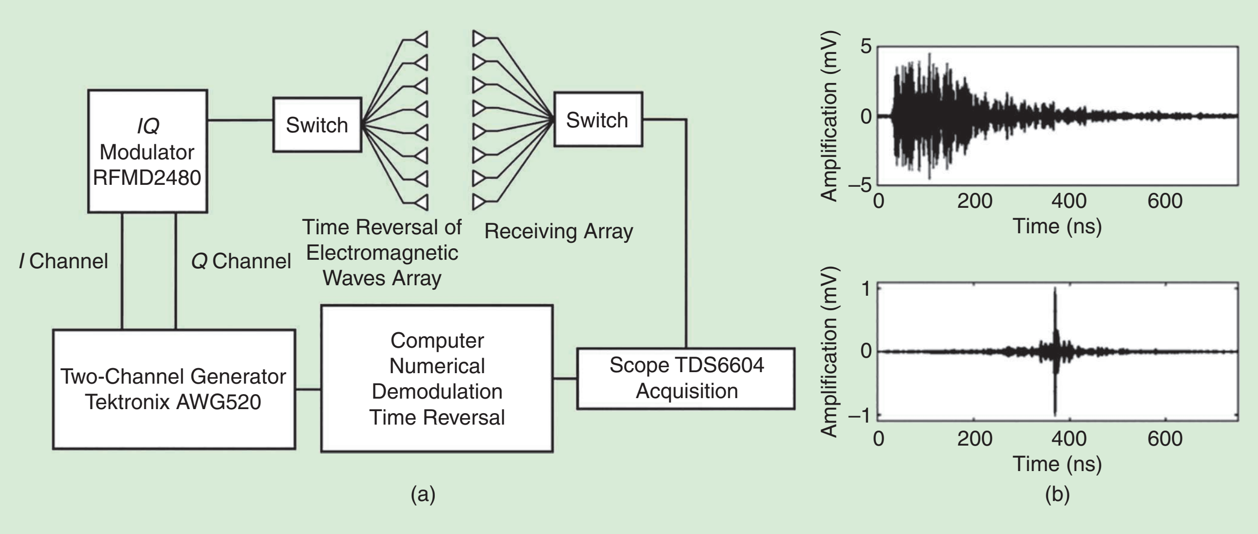


**FIGURE 2.** (a) The experimental setup to demonstrate the time reversal of electromagnetic via an eight-channel transceiver system. (b) The time compression results obtained after the time reversal of the original impulse response. Note the difference in the vertical range. IQ: in-phase and quadrature.

such as the transmission of optical images through scattering media by employing SLMs and wavefront shaping [16]–[19]. But more than that, it gave us ideas to solve the problem we had faced in the past with time reversal in wireless communications.

Our idea was to replicate SLMs in the domain of microwaves, control radio frequency waves in a passive way using only reflections, and hence solve the complexity of the massive MIMO systems we had been working on. Of course, using tricks from optics was out of the question: imagine translating a half-wavelength mirror that was half a wavelength away in the gigahertz range … Also, using an LCD was not a solution to us, requiring complicated and thick systems and significant power and resulting in something we knew was slow (with a 50–200-Hz refresh rate for SLMs). Fortunately, we were also active in the field of metamaterials and metasurfaces, and we knew that an electromagnetic resonator could impose a phase shift on waves upon reflection: this is how we started to develop electronically tunable metasurfaces for microwaves, that is, arrays of reconfigurable passive resonant reflectors, in 2012, with the goal of controlling wave propagation, rather than wave emission, for enhanced and greener wireless communications.

Our first prototype of what is now called an RIS was developed and tested during 2012, using our knowledge of metamaterials and the wave physics of complex media. We knew from our experience in ultrasound and optics that a binary phase unit cell was more than enough to efficiently shape waves propagating in complex media, and we designed one by using a patch sitting on a ground plane capacitively coupled to a parasite strip controlled by a p-i-n diode. Also, we wanted to make the RIS as low power and cost effective to fabricate as possible, and therefore we used standard printed circuit board fabrication and minimized the current dissipation to milliwatts per meter square. Finally, we fabricated the samples and controlled them using simple Arduino boards. During our experiments, we proved [20], [21] that passive control of Wi-Fi wave reflections on a surface of 100 unit cells covering less than 0.5% of the wall space in a typical office could improve antenna reception by a factor of 10, on average [Figure 4(a)].

**We strongly believe that innovation would go at a faster and more exciting pace if the connection between physics and wireless communications could be restored.**

Following this work, we submitted a paper to *Nature*, “Recycling Radio Waves With Smart Walls,” in which we described the concept and demonstrated the results of our RIS proposal. Again, if some referees were excited by the proposal, wireless communications experts were very much against it, questioning the work against MIMO and other established techniques. Publishing the paper was extremely complicated, and the work ended up in a more specialized journal, with a different title. As in the past, we decided to concentrate our follow-up efforts on more physics-oriented projects, and our subsequent papers mostly came out in physics journals [22]–[25]. Meanwhile, we filed patents, starting with a princeps in 2013 [26]. Shortly afterward, we created the company Greenerwave to push our ideas related to RIS toward the market, with the goal of making wireless communications more energy efficient and reliable.

Once more, the professional feedback we received was deceptive, and the wireless communications ecosystem, again including telcos, hardware manufacturers, integrators, service providers, and so on, was skeptical. Most questions dealt with the surface to cover for a given effect, the “nice to have” aspect of the technology, and the fact that wireless communications were working well enough. This time, the story was a bit different in the sense that nonspecialists embraced our ideas

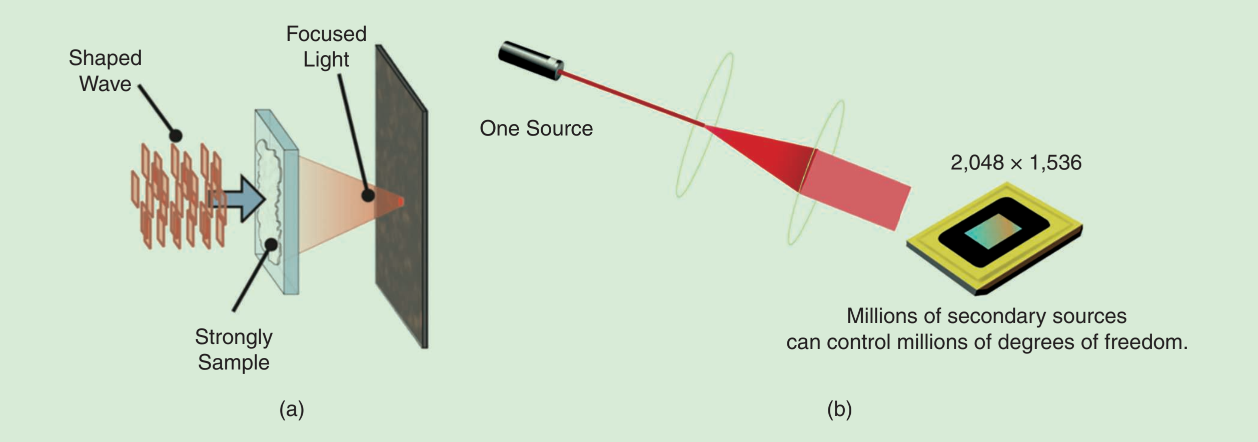


**FIGURE 3.** (a) SLM wavefront shaping can be used to concentrate a laser beam onto a sharp focal spot after light propagation through a strong scattering medium, such as a layer of paint. (b) This is a real paradigm change, as it does not require the precise manipulation of many sources but, rather, many controllable reflectors.

from the start, given their ecological aspect. So, we decided to go on anyway, and we pushed the idea toward industrialization, thinking that, at the very last, we could reach the consumer market. Unfortunately, this was not possible either since we faced a solid technological barrier: we needed access to the deep layers of transceiver chipsets to obtain robust and efficient feedback for our algorithms to control the RIS, and nobody was willing to grant it.

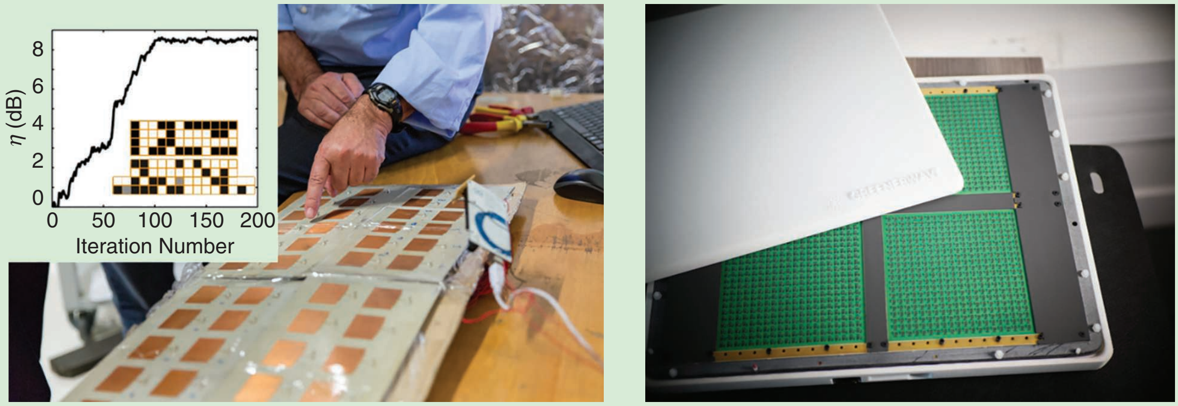
Greenerwave almost ended up in a worse situation than our previous startup, but this time, one of us, Geoffroy Lerosey, decided to take a leave from academia to save the company, convinced that the technology it was developing could not go in the wrong direction. Since RISs were clearly not to be adopted in a time frame compatible with a startup's lifespan, the goal was to find different markets and applications based on the same technological bricks: electronically reconfigurable metasurfaces and physics-based algorithms to control them. And this is how we began to develop the most energy-efficient, versatile, and low-cost beamforming millimeter-wave (mm-wave) systems for applications in 5G and beyond, satellite communications, and imaging radars [27]. These activities are going well, and the company has more than 30 engineers working on several projects. Again, the field of wireless communications is the least receptive one, with the space and automotive industries much keener to adopt our technology, but this time, given our demonstrations, we are sure that things will change sooner or later.

Nevertheless, we had to put our RIS activity on standby to survive. So, what a surprise it was when, in 2018, researchers in wireless communications came to us with the idea to write a paper on smart electromagnetic environments and how timely the idea was [28]. And what a surprise it is now to see how RISs are becoming one of the hottest topics in wireless communications [29]–[31]. Again, we are positive that our ideas are finally finding acceptance in the world of wireless communications. First, as pioneers, we benefit from this interest in the technology, as we participate in many collaborative projects that help fuel the company. Second, since electronically reconfigurable metasurfaces, that is, RISs, are at the core of our beamforming antennas, we are still in the race. For instance, our latest mm-wave RIS [Figure 4(a)] has been successfully tested by NTT Docomo, in collaboration with AGC, in Japan, with a real 5G base station [32]. Third, we have a strong intellectual property portfolio on the topic that will have some value should the technology be a real commercial success. Yet again, the question that comes to mind is how our proposal went so unnoticed years ago and, more generally, how ideas from physics could penetrate wireless communications faster and help foster innovation.

## CONCLUSIONS

In this article, we described two research fields that were initiated by specialists of waves physics and complex media. We briefly described how, convinced by the strong potential of these concepts, we tried to push these ideas in the field of wireless communications by submitting our work to specialized journals and creating companies devoted to this purpose. We underlined how complicated it was for us to evangelize to specialists and how puzzled we were every time we saw our concepts flourishing again, years later, in specialized literature and applications.

What we want to do with this piece is open a discussion aimed at solving the apparent issues that exist between physics and wireless communications. The faults are clearly shared. For instance, it is likely that the different vocabularies used in each domain play a crucial role. Similarly, physics is a world of small-scale laboratory experiments and conceptual



(a)

(b)

**FIGURE 4.** (a) The first RIS prototype for Wi-Fi, developed in 2012, with the insert showing the optimization, through one realization, of the energy received by an indoor antenna by using optimized reflections of radio-frequency waves on 100 unit cells. (b) A 1,600-unit-cell RIS for 5G mm-wave application developed by Greenerwave that was successfully tested as a passive access point extender by NTT Docomo and AGC.

proposals, strongly differing from the real problems encountered every day by electrical engineers in wireless communications, and this surely explains some of the misunderstandings and even some frustration. Also, the enormous number of journals and their ever-increasing specialization is likely responsible for separating the disciplines, and the publishers clearly do not advocate for interdisciplinary works. Finally, the rigid yet necessary architecture of wireless communications, with its standardization and regulation, does not accommodate the adoption of long-term ideas from physics.

Yet, we strongly believe that innovation would go at a faster and more exciting pace if the connection between physics and wireless communications could be restored. The story of the Bell Labs is an excellent example of how these disciplines have worked together in the past, and it is time for a new model to foster collaboration. This could start with a visit to our company to assess our disruptive mm-wave beamforming technology. We tell you it, is the future. This time, trust us.

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