INTRODUCTION BY EDITOR

Critical to the success of Marconi's pioneering work on radio telegraphy was the device needed to detect the radio telegraph messages on reception. Marconi finally settled on the "coherer." The invention of the device is often attributed to Oliver Lodge, a British physicist of the late 19th century. The detection properties of this device were, in fact, discovered by Edouard Branly, a French experimental physicist of the same period. As Dr. Dilhac makes clear in the following, Lodge himself attributed the signal detection properties of the coherer to Branly, coining the term coherer, and calling the device the "Branly coherer." The article clearly and succinctly discusses Branly's life, and describes the circumstances around which the coherer detection property was discovered by Branly. As pointed out by Dr. Dilhac, the physics behind the coherer long eluded scientists, and is just now, hopefully, becoming understood. All this makes for a fascinating study. I, personally, have enjoyed reading the article. I am sure all the readers of this column will find it interesting as well.

—Mischa Schwartz

EDOUARD BRANLY, THE COHERER, AND THE BRANLY EFFECT

JEAN-MARIE DILHAC, UNIVERSITÉ DE TOULOUSE (LAAS-CNRS AND INSA)

INTRODUCTION

Edouard Branly, a son of France, may be regarded as one of the very first pioneers in the field of wireless transmission. However, he himself denied being one of the fathers of radio communications; he is more accurately the discoverer of a physical effect (the Branly effect) that gave him the opportunity to devise an efficient wave sensor (the coherer) that permitted the invention of radio. Interestingly, he also contributed to the identification of the role of the aerial. Finally, what is called today the Branly effect is still largely unexplained and constitutes a subject of investigation.

THE GENESIS OF A DISCOVERY

Edouard Branly was born in 1844. After having performed brilliantly in classical secondary studies, he chose sciences and entered the Ecole Normale Supérieure (at that time Louis Pasteur was the head of studies of this university). In 1868 he was appointed as engineer (later deputy-director) of a physics laboratory at Paris Sorbonne University. He there obtained a doctoral degree in physics in 1873. His research field was then electrostatic phenomena in batteries [1]. In 1870, during the Franco-Prussian War, he served as a military engineering officer (during this war, the French Second Empire was replaced by the Third Republic). He then left the Sorbonne in 1875[1] for the newly organized Catholic University of Paris, the law of 12 July 1875 now permitting private universities. In 1880 it became *Institut Catholique*, as the term *university* was then reserved again for state institutions. Leaving the Sorbonne for a Catholic university raised the risk of marginalization in the secular French Republic of that time.[2] Moreover, while a modern *research* laboratory installation was initially expected by Branly [2], he would only benefit from the equipment of a *teaching* laboratory located in a former dormitory subject to vibrations linked to the traffic of the nearby rue de Vaugirard. Branly would have to wait 60 years before benefiting from a modern building for his laboratory. One possible explanation is that after the 1870 war, the building of the *Sacré Coeur Basilica* was decided on and diverted a lot of the diocese of Paris funds from institutions like the Institut Catholique [2].

In 1877 he was again a student, but at the faculty of medicine of Paris, consequently interrupting his research activities. In 1882 he was awarded a physician's degree after preparing a thesis on hemoglobin concentration analysis in blood by optical means.

At the end of the 1880s, Branly went back to his research in pure physics, concentrating on the influence of irradiation on the electrical conductivity of various substances. In June 1890 he used a Wimshurt machine to create sparks and to study the electrostatic discharge of various substances submitted to the light from the spark (i.e., UV-rich radiation) [3]. Branly had devised a first circuit to create sparks using the Wimshurt machine, and then a second very simple circuit: a Daniell battery, a galvanometer,

[1] *Partly because he refused to marry the daughter of his faculty head.*

[2] *This may explain the fact that, despite the proposals made as early as 1904 and later in 1915 by the Stockholm Academy of Science, Branly was never awarded the Nobel Prize, the French experts consulted by Swedish academicians having made other proposals [2].*

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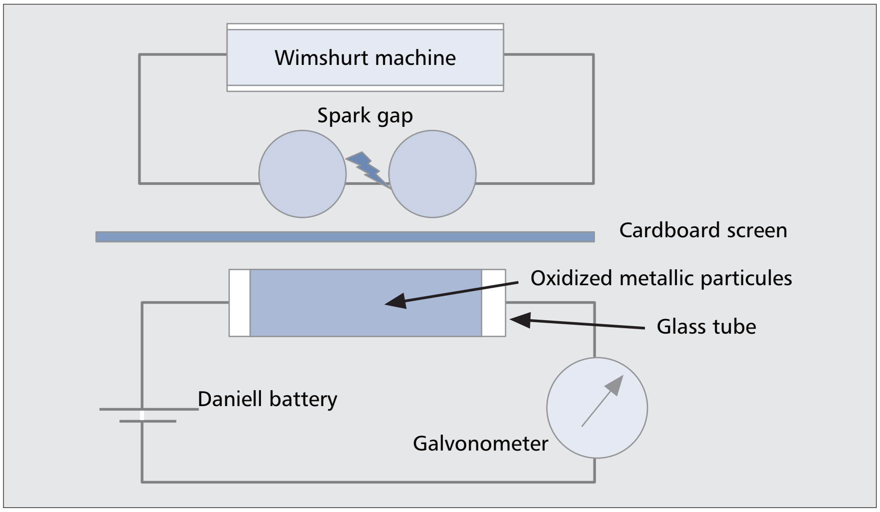

■ **Figure 1.** *Schematic of Branly's experiment.*

and a metallic disk all wired together in series. The disk was initially electrically charged. The two circuits were initially close to each other, so the light from the spark illuminated the disk. Following the spark, in some cases a dramatic increase in disk conductivity could be detected by the galvanometer. In November 1890 he replaced the disk by a tube filled with oxidized Zn particles.[3] Just after the spark, it was again found that the conductivity of the tube was increased by several orders of magnitude. He then inserted various obstacles between the spark and the tube in order to evaluate the properties of the propagation of the invisible part of the light (i.e., UV) between spark and tube. At one point he inserted a piece of cardboard and noticed that the effect persisted (Fig. 1). He then put the circuit made of the battery, galvanometer, and tube in another room, 20 meters away, separated by thick walls and a courtyard from the Wimshurt spark-emitting circuit: the effect persisted while neither the light from the spark nor its sound could be seen or heard by Branly sitting by the tube while his aide Rodolphe Gendron was operating the electrostatic machine. A small shock was found to restore the initial conductivity value, while a new spark allowed the phenomenon to be repeated. His paper on this work was published in French [4] on 24 November 1890.[4]

Branly called the detecting device (the tube filled in with metallic particles) a *radioconductor*: this is likely to have been the first use of the prefix *radio* in the context of wireless communications [5]. For Branly, the term radio referred to the electric *radiation* from the spark. However, as early as January 1891, Branly followed the November 1890 paper with a publication on the role of aerials (he did not use the term) in relation to the distance of transmission, together with the effect of a Faraday cage [6]. The transmission distance was then (1891) on the order of 80 meters [3].

BIRTH OF THE COHERER

What is referred to today as the *Branly effect* is an electrical conduction instability appearing in a slightly oxidized inhomogeneous metallic conductor (usually placed in a glass or ebonite tube and submitted to moderate mechanical pressure) when an external disturbance is applied: the initial high electrical resistance of many megohms due to the naturally oxidized surfaces then falls to a relatively low value of a few ohms. A mechanical shock restores the initial high resistance value [7]. The disturbance can be a high current (phenomenon discovered in 1835 by P. S. Munk using the discharge current of a Leyden jar), but in 1879 D. E. Hugh-

[3] *He observed the same phenomenon with Fe, Al, Cd, and Bi.*

[4] *At that time, publishing in* Comptes-Rendus de l'Académie des Sciences *was a fast process as there was no refereeing. Reports of Branly's results were published in English in the (London)* Electrician *in June and August 1891 [16].*

es appears to have discovered that the above conduction instability could also be induced by an electrical spark at a distance. However, the Royal Society of London was not convinced, and his results were only published in 1899 [8]. Finally, in 1884 T. Calzecchi-Onesti discovered that the electrical conductivity of metallic powders increases after having been submitted to a sufficiently high voltage.

In 1894 British scientist Oliver Lodge repeated Hertz's 1887 experiments on radiation from sparks, but using a Branly tube as a detector. This was much more sensitive than Hertz's technique using a wire loop containing a small gap within which electromagnetic waves were induced, having themselves been created by a first arc. Hertz's experiments, carried out after the publication of Maxwell's theory, were designed to verify Maxwell's theory and to demonstrate the propagation of electromagnetic waves over a few meters. These tiny (much less than a millimeter in length) sparks could only be seen in darkness, and in some cases a magnifier was even required. Consequently Hertz mentioned in a letter that electromagnetic waves were unsuitable for remote signaling due to the difficulty of detection [9].

Lodge improved Branly's tube by adding a relay automatically triggering a shock after a decrease in electrical resistance, making the device usable for wireless transmission. Lodge coined the term *Branly's coherer* (from Latin *cohaere*, to stick) referring to his first understanding that the modifications in resistance were related to small movements of the particles, considered as dipoles, due to electrostatic effects. These movements were supposed to form conductive fragile chains, therefore allowing the percolation of electricity through the powder, a shock easily destroying these chains. Edouard Branly did not believe this explanation, arguing that the effect persisted even if the oxidized metallic particles were stuck in paraffin, resin, or wax, and therefore were unable to move. For this purpose, he also used large steel balls a few centimeters in diameter arranged in a single chain, and demonstrated there again that the effect persisted. The term *coherer* was not accepted by Branly but was nevertheless widely accepted.

Lodge and Branly later collaborated in an attempt to identify the underlying physical mechanisms.[5] Neither of them really focused on wireless telecommunications applications. It must also be mentioned that it was only in response to Lodge that Branly — mainly an experimenter — tentatively devised a first theoretical explanation of the effect he had discovered, based on ether between grains. He did not refer to Hertz waves before 1895 [10], but it is worth noting that Hertz's work was not fully accepted until 1892 after its reproduction by other scientists [11].

On the other hand, it must be stressed that without the coherer, the birth of wireless communications would have been greatly delayed into the next century. The coherer was the sensitive sensor required by those following Branly: in contrast to the detecting loop, the coherer was an on/off sensor delivering an electrical output, well adapted to binary codes, and likely to be connected to electromechanical printing devices through an electrical relay [3]. In 1895 both Popov and Marconi started their radio transmission activities using coherers. More generally, most of the experimental work in the field of wave propagation during the last decade of the 19th century and the start of the 20th used a coherer as a wave sensor [5]. When the first commercial wireless links came into operation at the turn of the century, reliable coherers were commercially available [5].

In 1898 Ferdinand Braun improved the usual architecture of transmitters by implementing a sparkless antenna loop magnetically coupled by a transformer to the power spark loop.[6] The previously insurmountable 15 km limit for transmission range with which Marconi was confronted could now be exceeded [9]. However, pulsed waves were still used, and the coherer remained the best detector, surviving the first generation change in wireless telecommunications (i.e., the transition toward long distances). In 1899 Guglielmo Marconi realized the first wireless transmission over the Channel [6] between England and France. The text of the dispatch is as follows [6]: *M. Marconi envoie à M. Branly ses respectueux compliments par le télégraphe sans fil à travers la Manche, ce beau résultat étant dû, en partie, aux remarquables travaux de M. Branly. (Mr. Marconi sends to Mr. Branly his regards over the Channel through the wireless telegraph, this nice achievement being partly the result of Mr. Branly's remarkable work.)*

In 1906 Braun replaced the coherer by a crystal of Galena used as a rectifier. As with the coherer, it was a cheap device, easy to build, very sensitive, and also based on unknown physics principles. However, the crystal rectifier was very well adapted to the continuous waves

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[5] *It is worth mentioning that J. J. Thomson only discovered the electron in 1897.*

[6] *In 1909 Braun received the Nobel Prize for Physics together with Marconi for his contribution to wireless telegraphy.*

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about to be utilized in radio for analog (voice) transmission, while the coherer was useless in that case. With the added inventions of the vacuum rectifier by John Fleming in 1904 and the triode by Lee de Forest in 1906, wireless technology rapidly evolved, and the coherer fell into oblivion.

BRANLY AND THE TELECOMMUNICATIONS INDUSTRY

After his discovery, Branly did not pursue further research specifically devoted to wireless telecommunications such as trying to increase the distance of communication, or identifying the role of the aerial or of wave frequencies [12]. Moreover, he did not file any patent and freely distributed *Branly tubes* to all requesting them, concentrating on the improvement of its sensitivity and stability.[7] Nevertheless, he participated in experiments of long distance wireless transmission, both in 1898 at the Eiffel Tower with Eugène Ducretet,[8] and in 1899 at Ouessant Island on the Atlantic coast. In 1912 he refused the position of technical advisor in one of Marconi's companies [12] when Guglielmo Marconi himself paid a visit to Branly's laboratory at Institut Catholique [6].[9] Both Marconi and Branly were elected members of the Academia dei Lincei in Rome, Italy (later Pontifical Academy of Sciences), Branly in 1902. However, Branly did briefly participate in the commercialization of telecommunications through the *Société Française de Télégraphes et Téléphones sans Fil* created by Victor Popp in 1901 [12]. Unfortunately, in contrast to Great Britain, the field of telecommunications was then in France a state monopoly, and the company had to stop its activities in 1904 despite — or because of — successful first deployments.

EDOUARD BRANLY'S ACADEMIC ACTIVITIES AFTER THE INVENTION OF THE COHERER

Between 1900 and the second World War, Edouard Branly's celebrity was high in France, even if today it is much more limited, not to mention that he is nearly unknown in countries outside of France. As an example, he does not appear in the *New Dictionary of Scientific Biography*. The celebrity in France was due to the fact that Branly was considered one of the fathers of radio communications. In 1911 he was therefore elected to the French Academy of Sciences in competition with Marie Curie (he had previously been a candidate twice). The election was a tough one, fought out between supporters of both candidates. One of the issues under debate was the fact that a woman was running for election. An academic clerical group supported Branly, while progressive scientists lobbied for Marie Curie. An unusually large public managed to attend the final session of the Academy during which the ballot was organized. To prevent incidents, Armand Gautier, who was chairing the session, instructed the ushers to "allow everybody in… except women of course"! Branly was elected one ballot ahead of Marie Curie, who never competed again. The first woman to be elected as a full member was Yvonne Choquet-Bruhat in 1979.

In 1915, during World War I, Branly devised an optical telegraph operating in the infrared, allowing transmissions without the risk of messages being intercepted; experiments with transmissions up to 20 km were carried out [2].

In 1932, thanks to a grant from the famous and rich François Coty, who made his fortune creating and selling perfumes, a new laboratory for Branly (then 87) was at last inaugurated. The new laboratory had been devised by Branly's son-in-law Paul Tournon, and incorporated special devices such as a large Faraday cage and stone pillars to eliminate parasitic vibrations. This laboratory is today a small museum located within Institut Catholique de Paris (21 rue d'Assas) devoted to Edouard Branly's research and achievements. From the beginning it was designed for that purpose, following Coty's will.

For a few more years, Edouard Branly pursued his research projects there. In 1934 Sara Delano Roosevelt, mother of Franklin Delano Roosevelt, then President of the United States, visited him. In December 1935 he published his last paper [2] about a new design for medical thermometers where the mercury-filled glass bulb was replaced by a metallic Ni bulb.

Branly died in 1940 at the age of 96. He was survived by his two daughters and five granddaughters. The funeral was celebrated in Notre Dame de Paris, and was attended by the President of the French Republic Albert Lebrun.

THE FATE OF THE BRANLY EFFECT

With the absence of subsequent industrial applications, the lack of accuracy of the coherer as a scientific instrument, and the difficulty of elaborating a definitive theory despite the comprehensive experimental work performed by Branly, the Branly effect fell into oblivion. Electrical transport properties were mainly studied within solid-state physics during the first half of the 20th century. However, in the 1950s the Branly effect was again utilized in Japan within the first wirelessly operated toy [13].

Several explanations have been suggested to explain the Branly effect [7], first at the microscopic scale: electrostatic attraction of the grains, electrical breakdown of the metallic oxide layers, the tunnel effect, and, finally, local welding of the grains through electrothermal coupling and melting of micro contacts between grain surfaces. Macroscopic phenomena were also invoked, such as electrical percolation. New characterization methods, such as 1/f electrical noise evaluation or infrared observation of conduction paths, were used, suggesting new theories [7]. However, difficulties due to the quantitatively weak reproducibility of the phenomenon together with the high number of influencing parameters such as aging, temperature, and grain materials and size explain why, at the end of the 20th century, the theory of the Branly effect was still to be established [14]. This was despite the fact that, as early as the 1960s, the emerging physics of granular materials triggered new scientific interest in relation to this old effect. Since then, this interest has constantly increased, as granular media are present in many fields. For instance, mixtures of solid propellant for some rockets, incorporating aluminum particles, may be affected by electromagnetic waves created by nearby lightning.[10] More recently, and on another scale, nanoelectronics also started using grains in various structures, either submitted to high currents due to electrostatic discharges or exposed to strong electromagnetic interferences [15].

A recent publication [7] is very convincing in demonstrating the key contri-

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[7] *He devised in 1902 a device that was more efficient than the classical coherer: the* trépied.

[8] *Eugène Ducretet was an industrialist specializing in the construction of technical equipment. The 1898 successful Morse signaling from the Eiffel Tower saved it from demolition.*

[9] *Branly and Marconi last met in 1932 during the XIth International Telegraphic Conference in Paris, for which they co-chaired the gala dinner [2]. Marconi died in 1937. He was survived three years by Branly.*

[10] *As early as in 1901 Branly was asked by the French Ministry of War to examine the effects of wireless telecommunications equipment on gunpowder stored in warehouses.*

(Continued from page 24)
bution of local welding to the Branly effect. The authors, E. Falcon and B. Castaing, strategically decided to eliminate side contributors to the Branly effect such as percolation, or the alternative nature of the applied or induced voltage, and to devise an experimental arrangement where a limited set of parameters would be involved. Similar to Branly in some experiments, they used a single chain of steel beads submitted to dc currents, and measured the voltage drop and thus the resistance across various numbers of beads. Thus, they concentrated on electrical transport at a microscopic level linked to the dc Branly effect. They observed that while initially highly resistive, above a certain voltage the chain resistivity dramatically decreases. They also derived a theoretical model of this effect, and thereby both experimentally and theoretically demonstrated that local welding is one of the contributors to the effect. It originates from an electrothermal coupling in the vicinity of the micro contacts between each bead. These welded contacts are, of course, likely to be broken by a shock. However, without a shock, this welding is irreversible, and the chain will exhibit high and nearly constant conductivity whatever the future current levels. Unsurprisingly, the whole process was found to be reproducible.

CONCLUSION

During his life, Branly constantly denied being the *inventor* of radio [11], claiming that as a *scientist* he had only discovered an effect that had permitted others, like Popov, to develop wireless transmission.[11] On the other hand, he was one of the earliest promoters of the remote control of equipment. During a largely publicized demonstration on 30 June 1905 at *Palais de Chaillot* in Paris he demonstrated the possibility to remotely and wirelessly turn light bulbs on and off or activate various electromechanical apparati including motors.[12] He made a publication on that topic in *Compte-rendus à l'Académie des Sciences de Paris* in March 1905.

What is today called the Branly effect refers to a set of phenomena some of which were discovered before Branly. However, Branly was undoubtedly the first to publish about the effect of a spark that is, in modern words, the effect of an electromagnetic wave. Therefore, through the coherer and the demonstration that radio waves could easily be detected over long distances, he permitted early developments in wireless telecommunications. Finally and surprisingly, because of both its own intrinsic complexity and its potential involvement in modern technology, the Branly effect is today still a subject of investigation.

ACKNOWLEDGMENTS

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Most of the references below are in French. However, [7] and [16] present in English a discussion about past and recent explanations of the Branly effect, and detailed studies of the first age of radio. For an account of the private life of Branly, the book written by Branly's daughter [6] is the essential source.

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BIOGRAPHY

JEAN-MARIE DILHAC [SM] is a professor at Institut National des Sciences Appliquées of Toulouse University, where he served as head of the Department of Electrical and Computer Engineering (2004–2008). His main teaching fields are related to electronics, signal processing, and telecommunications. A side activity is devoted to the history of computing and telecommunications. He also serves as a member of the IEEE Communications Society's History Committee. He is a senior scientist at LAAS-CNRS research laboratory. His present research activities are related to energy management in wireless sensor networks applied to either structural health monitoring or in-flight testing for aeronautical applications. He is in charge of many collaborative research programs in connection with Airbus.

[11] *The coherer was the first solid-state device used in electronics [16].*

[12] *5000 spectators were present [2].*

LETTER TO THE EDITOR

Comments on "Partial-Response Coding …," by H. Kobayashi

G. David Forney, Jr., Massachusetts Institute of Technology (forneyd@comcast.net)

Thank you for the interesting and authoritative article by Hisashi Kobayashi [1] on the history of partial-response, maximum-likelihood (PRML) technology, which became an industry standard for magnetic recording in the 1990s. To expand upon that account, your readers might like to know that, as far as I am aware, the first commercial implementation of a version of PRML was in 1969 in the Codex AE-96, a single-sideband 9600 b/s telephone-line modem that used 1 – D2 partial-response signaling. This technique was described in a 1971 patent [2], and in the last section of my 1972 paper [3, pp. 373–75]. Practically, it gained about 3 dB, and extended the product life of the AE-96 by several years. Theoretically, it led me to think about maximum-likelihood sequence detection for general intersymbol-interference channels, which eventually led to [3].

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