A reprint from

# American Scientist

the magazine of Sigma Xi, The Scientific Research Honor Society

# Random Paths to Frequency Hopping

*Actress Hedy Lamarr famously co-patented a widely used secure-communication technology, but popular accounts ignore her many predecessors.*

Tony Rothman

In an age when we ought to know better, the public perception of the evolution of science and technology retains the flavor of old just-so stories. In these tales, great discoveries or inventions are typically made by a single person. The hero, often an outsider working in splendid isolation, experiences a cinematic eureka moment when everything becomes blindingly clear. History is forever altered, and on we go until the next pivotal genius appears.

The truth is generally the opposite: Those who work in science and technology see that ideas are not unique; every conceivable approach to an outstanding problem is attempted by the community; contributions flow from every quarter; progress takes place incrementally; and multiple researchers inevitably hit on the same idea, producing discoveries that are simultaneous or nearly so. Assignment of credit is rarely clear-cut or generously inclusive. The old adage that "every discovery is named for the last person who discovered it" strikes closer to the mark than we might like to admit. Who receives acclaim depends, too, on whose story serves political interests, fits a convenient cultural narrative, or simply registers as sufficiently sensational.

An archetypical case is the invention of radio. To American—and Italian—schoolchildren, Guglielmo Marconi was the responsible party. In England, Oliver Lodge is accorded precedence; in Russia, Alexander Stepanovich Popov; in India, Jagidish Chandra Bose. In New Zealand, credit mostly goes to Ernest Rutherford. None of these answers is wrong, exactly, but neither is any one of them exclusively right. All of these inventors created comparable devices within about a year of 1894.

Recently, attempts to address historical slights have lapsed instead into another kind of just-so story. Over the past two decades it has become standard, even fashionable, to credit the invention of Wi-Fi, Bluetooth, and even cell phones to 1940s movie star Hedy Lamarr. The story is appealing and exotic: Lamarr, an intelligent woman and amateur inventor, was shoehorned into a Hollywood culture that valued her as a screen siren and nothing more. Since a Google doodle was devoted to the actress in 2015 and *Bombshell*, a documentary about her, was released in 2017, the popular history has become chiseled in marble—well, let us say, arrayed in bits.

It is true that Lamarr and her unlikely partner, the radical modernist composer George Antheil, hold a patent for an important radio-transmission method that finds its way into several modern communications technologies, including Bluetooth. But it is equally true that their patent was hardly the first in this area. It is further true that the earliest operational systems employing this technique were created after World War II independently of their patent, and the essential idea can be traced back nearly to the birth of radio itself. If Lamarr and Antheil's attorneys had performed a more diligent patent search, different doodles might well have graced Google.

## The Actress and the Composer

The tale of Hedy and George might have been written by Arthur Conan Doyle, or even Graham Greene. Briefly: At an early age Hedy Lamarr, born Hedwig Kiesler in Austria, married Fritz Mandl, a Nazi sympathizer and Austria's leading munitions manufacturer, on the eve of World War II. Lamarr escaped this unhappy union (as she tells it, disguised as a maid whom she had drugged) and soon after ended up in Hollywood. Through a mutual interest in the obscure field of applied endocrinology, she met George Antheil. Revealing that she possessed a flair for inventing weapons, Hedy shared with him an idea for a secure torpedo guidance system that employed a novel technique known as *frequency hopping*.

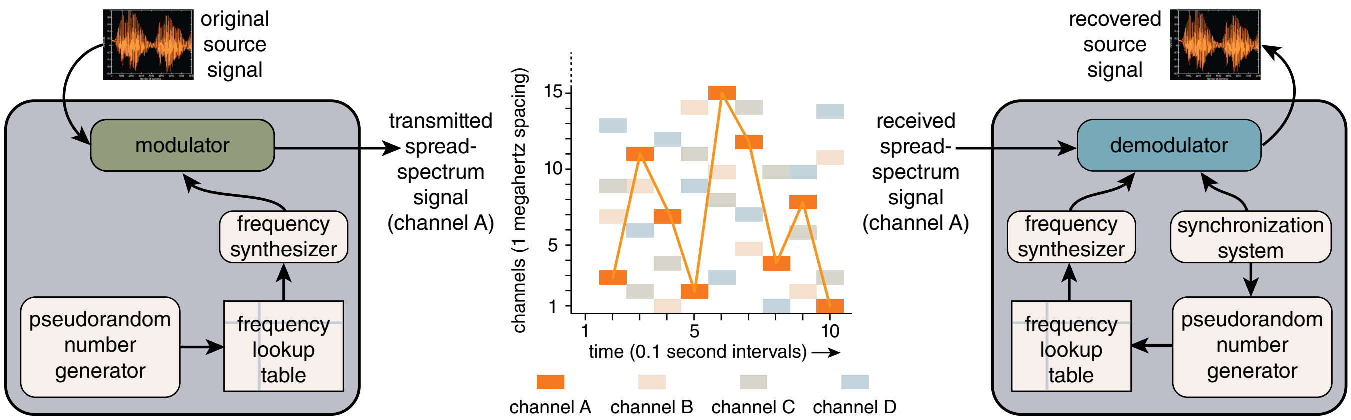
Frequency hopping is the simplest version of a radio transmission technique today known as *spread-spectrum technique*, which refers to any method that widens the frequency band of a signal. Normally, radio stations broadcast on a single carrier frequency, which makes eavesdropping deliberately easy: You tune your radio to the correct frequency and receive the programming. By contrast, frequency hopping prevents the interception and decipherment of a transmission by shifting the carrier frequency in a predetermined, usually pseudorandom fashion—in other words, in a way that appears random but is produced by a deterministic algorithm. A receiver hopping around in synchrony with the transmitter can pick up the message, but an eavesdropper tuned to a single frequency will hear only a blip as that bit of message flashes by. Frequency hopping is largely jam-proof as well. If the frequencies are spaced widely enough, any jam-

**Actress Hedy Lamarr (*bottom*) and composer George Antheil (*top left*) patented a form of frequency hopping for secure communication. Popular articles have spread awareness of their efforts but have tended to overlook many other important contributors, from cryptographer Gilbert Vernam (*top*) to Bluetooth inventor Jaap Haartsen (*middle right*).**

illustration Barbara Aulicino; Images: ahistoryblog.com/Bruce Ware Allen; © Union européenne 2012/EC Service Audiovisuel/Christoph Boeckheler; U.S. Patent Office; Pictorial Press LtD/Alamy

*Tony Rothman is a cosmologist in the department of applied physics at New York University Tandon School of Engineering. He is a coadjutator of Les Amis de George Antheil. He once wrote a play about Hedy Lamarr and George Antheil, but he attempts to distinguish fantasy from reality. Email: tonyrothman@gmail.com*

Fig. 4.
Fig. 5.
Hedy Kiesler Ma
George Antheil
WESTERN EUROPE EDITION
THE STARS AND STRIPES
Unofficial Newspaper of U.S. Forces
Vol. 2—No. 128 1 Fr.
Hedy Adds New Twist
Actress Invents Control De
With Torpedo Idea, Has
HOLLYWOOD, Nov. 18 (AP)—It could not have been a press agent's stunt, because the timing was too perfect, but the report from London that film actress Hedy Lamarr had patented a radio steering device for torpedoes at least had a patent to back it up.
In an interview, Hedy modestly admitted she did only "creative work
thell, "did the really important chemical part."
for the British. A radio controlled torpedo, I thought would do it."
Hedy asserted that the control device works on aerial as well as submarine torpedoes.
She said it works on anything
gether all the little thingamabobs




**In frequency hopping, a source signal is sampled at short time intervals; each interval is modulated with a different frequency that is selected using a pseudorandom number generator (*left*). The unpredictable hops in frequency (*center*) make the message difficult to intercept and allow the transmission of overlapping channels. The receiver (*right*) reverses the randomly generated frequency shifts, using synchronization signals exchanged with the transmitter, and retrieves the original signal. (Information provided by Glenn Babecki.)**

Barbara Aulicino

ming signal will interfere with only a small part of the message.

Trained as an actress, Hedy lacked the technical expertise to put her idea into practice. George was likewise no engineer, but two decades earlier he had written a concert piece, the notorious *Ballet Mécanique,* which included parts for synchronized player pianos. That background instantly triggered a thought: He would place a player-piano roll punched with 88 rows of randomly placed perforations in the transmitter to control the hopping among 88 radio frequencies; he would place an identical roll in the receiver; and then he would synchronize the two. Why 88? That's the number of keys on a piano.

An invention notebook in George's handwriting reveals that he was influenced by Philco's 1939 Mystery Control, the first commercially available radio remote controller. With the help of Samuel Mackowen, a California Institute of Technology engineer, George ironed out the bugs in their invention, and he and Hedy applied for a patent in June 1941. Considering the familiarity with patent conventions and technical radio concepts on display, it seems likely that Mackowen wrote the patent itself. On August 11, 1942, Lamarr and Antheil received U.S. Patent 2,292,387 (issued to Lamarr under her married name, Hedy Markey) for a "secret communication system."

Despite the novelty of their approach, the pneumatic player-piano mechanism made their system unwieldy—and certainly unworkable in battle. Antheil made strenuous lobbying efforts to get the invention adopted by the Navy, but it was shelved. According to George, the Navy brass thought he wanted to put a player piano in a torpedo. Nevertheless, one frequently encounters claims (for instance, in Richard Rhodes's 2011 book *Hedy's Folly*) that because of its military potential, the Lamarr-Antheil patent was classified by the Navy. Although it adds to the story's drama, that detail does not appear to be true.

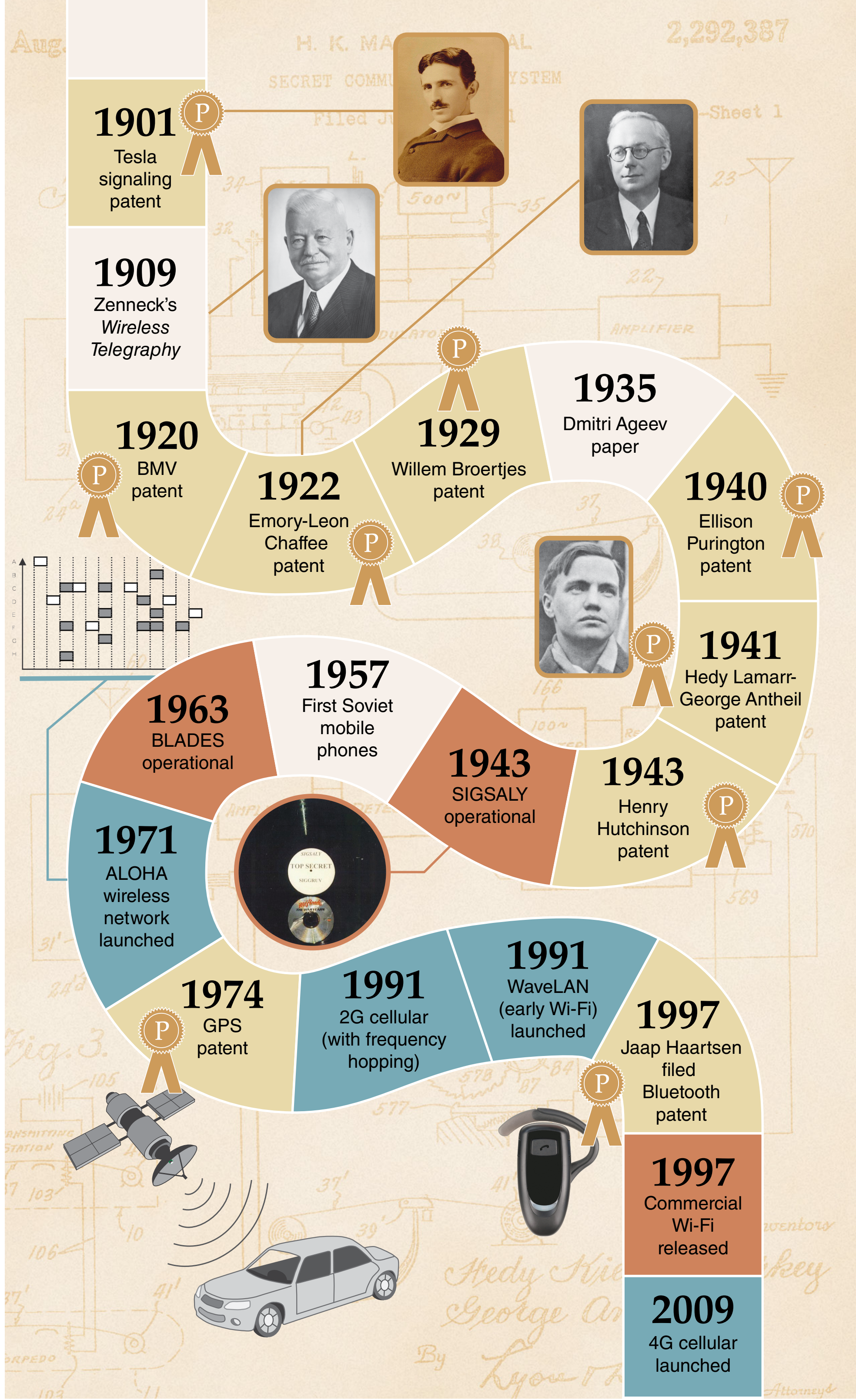
The authors of the *Spread Spectrum Communications Handbook* state that the patent was processed routinely with no imposition of secrecy. A tiny *New York Times* notice dated October 1, 1941, did report that the National Inventors Council "classed Miss Lamarr's invention in the 'red-hot' category," but two days later Lamarr and Antheil's patent attorneys, Lyon and Lyon, wrote a letter (provided to me by Antheil scholar Mauro Piccinini) to their clients making a contrary claim:

> We noticed considerable publicity to the papers recently resulting from statements of Col. Lent of the National Inventors Council. This publicity is rather puzzling in view of the fact that the Patent Office has not issued a Secrecy Order. It is also difficult to understand why the Secrecy Order has not been issued in view of the fact that the Examiner has found nothing antedating the invention.

George himself apparently didn't believe the invention was classified: He gives the patent number in his 1945 autobiography *Bad Boy of Music* and is under the impression that anybody can get a copy of the thing by mailing 10 cents to the Patent Office. In addition, in their letter Lyon and Lyon also expressed surprise that "the Patent Office did not discover more pertinent patents than those cited." That surprise turned out to be well-founded.

Claims and counterclaims have been made as to whether Lamarr originated the frequency-hopping scheme or learned of it in meetings at Fritz Mandl's firm, the Hirtenberger Patronenfabrik. In *Bad Boy*, George affirms that she got her education at those meetings, and although he is not exactly the world's most reliable memoirist, he could hardly have received the information from anyone but Hedy. Robert Price, an engineer at Massachusetts Institute of Technology's Lincoln Laboratory and a pioneer of spread-spectrum technology, interviewed Lamarr. He told me that he came away convinced that she had heard the idea in her husband's boardroom, and with tongue somewhat planted in cheek, Price called her "the Mata Hari of World War II." Still, one must be mindful of historical gender roles—of how Lamarr might have presented herself as well as how her statements might have been received.

The notion that Lamarr's patent might have begun with an idea she heard from her former husband's colleagues is dismissed in the documentary *Bombshell*, where the filmmakers claim that German engineers at the time were unaware of the technology. However, Hans-Joachim Braun, whose 1997 article in *American Heritage of Invention and Technology* spurred the original interest in Lamarr's role as an inventor, informed me that documentary evidence in the Bundesarchiv-Militärarchiv in Freiburg shows that German engineers before World War II were aware of frequency hopping, although they lacked the means to put it into practice.




**More than a century separates Nikola Tesla's frequency-based "method of signaling" from today's widely used spread-spectrum data transmissions. The researchers and inventions listed here are just highlights of a story that defies simple narratives. Even well-formed concepts often follow convoluted paths to implementation: Roger Easton's key patent for GPS ("Navigation system using satellites and passive ranging techniques") was granted a full 45 years ago.**

Illustration Barbara Aulicino; Thumbnails: Wikipedia Commons; AIP Emilio Segrè Visual Archives; Donald E. Mehl; Nick Fielding/Alamy

**Great Minds Think Alike**

At any rate, Hedy and George were hardly alone. In September 1940—a year before Lamarr and Antheil filed their patent application—Ellison Purington, who had done graduate work in physics at Harvard University and had worked on torpedo guidance systems at the Hammond Laboratory during World War I, filed an application for a "System for Reducing Interference." In this patent (U.S. Patent 2,294,129), granted in 1942, Purington proposes "wobbling" the carrier frequency to reduce the ability of other transmitters to interfere with the signal. There seems to be no substantial difference between Purington's frequency wobbling and Lamarr's frequency hopping, except that frequency-hopping systems hop over a much wider bandwidth than Purington envisioned.

Purington's eureka wasn't the only one. In January 1943, five months after Lamarr and Antheil received their patent, U.S. Army Signal Corps officer Henry Hutchinson applied for a "speech privacy apparatus" relating to a "means of maintaining secrecy in communication, particularly in telephone circuits." Like the Lamarr-Antheil patent, Hutchinson's employed frequency hopping; instead of player-piano rolls, his scheme utilized cryptographic machines to produce a pseudorandom hopping sequence on demand. In this case, the application *was* held under a secrecy order until 1950, when Hutchinson was awarded U.S. Patent 2,495,727.

In an unusually noble act for the time, Hutchinson listed a dozen previous patents for secret communication systems dating back to the 1920s. Virtually all of them had emerged from Western Electric, the American Telephone and Telegraph Company (AT&T), or Bell Labs—the third having been formed in 1925 as a result of the consolidation of the first two. A number of the authors, including well-known pioneers of communications Harry Nyquist and Ralph Hartley, later participated in the top-secret Project X during World War II. Declassified patents from Project X also reveal a few additional pieces of prior art from the 1920s and 1930s. Glenn Babecki, an electrical engineer, and I have examined these early patents.

Every one of them proposes ensuring the secrecy of a message by hopping unpredictably among a group of low-frequency audio channels. In the majority of patents, the scrambled message is then transmitted by telephone line or radio along a single high-frequency carrier wave, making the system secure but not jam proof. Because the carrier wave is held at a constant frequency, we would probably not refer to this group of patents as frequency-hopping patents in the modern sense. On the other hand, Hutchinson's list reveals that in 1940 Purington had already received a patent (U.S. Patent 2,204,050) for a secrecy scheme that incorporates the frequency-wobbling concept and so could be called frequency hopping. An even earlier Purlington patent (U.S. Patent 1,992,441, from 1935, overlooked by Hutchinson) also utilizes frequency wobbling.

Despite his honorable intentions, Hutchinson missed the proposal of Dutch inventor Willem Broertjes, who on October 11, 1929, submitted a patent application in Germany for a "Method of Maintaining Secrecy in the Transmission of Wireless Telegraph Messages." A month later Broertjes filed an application in America, and in 1932 he was awarded U.S. Patent 1,869,659. In it, he writes that

> The known methods of maintaining secrecy operate, in most cases, with codes or cryptograms and with a periodically modified transmission frequency, which is received by means of a receiving apparatus, the tuning of which is modified in synchronism.

According to Broertjes, then, the idea of changing transmission frequencies is already commonplace, but he argues that this approach does not prevent the interception and decipherment of the message, because a broadband receiver could pick up all the frequencies. As Lamarr and Antheil did later, Broertjes then proposes a system in which a number of "working frequencies," known to the sender and receiver alone, can be varied in a "random or variable manner," or even left out. "In a method of this kind," he writes,

> secrecy is ensured by reason of the fact that an unauthorized receiver which at first, is tuned in to only a single frequency length, picks up only disconnected portions of the message.

The Broertjes patent can be faulted in that the operation of the receiving mechanism is left largely as an exercise for the reader. The transmitter includes a "code wheel" that selects a new frequency each time a telegraph key is depressed. One can only assume that the receiver contains a duplicate wheel, but Broertjes prefers manual operation, so it remains unclear how he intends synchronization to be effected. Despite its flaws, Broertjes's invention proves that the frequency-hopping concept was available in Germany well before the war.

But the fundamental law of invention and discovery is the "infinite chain of priority," which ensures that someone else always did it first. In this case, the chain included Emory-Leon Chaffee, a Harvard University physicist who had worked with Purington at Hammond Laboratory. In an application filed in 1922 but granted only in 1927 (U.S. Patent 1,642,663), Chaffee describes a "System of Radiocommunication" that proposes wobbling the carrier frequency in an "erratic manner" in order to provide secrecy.

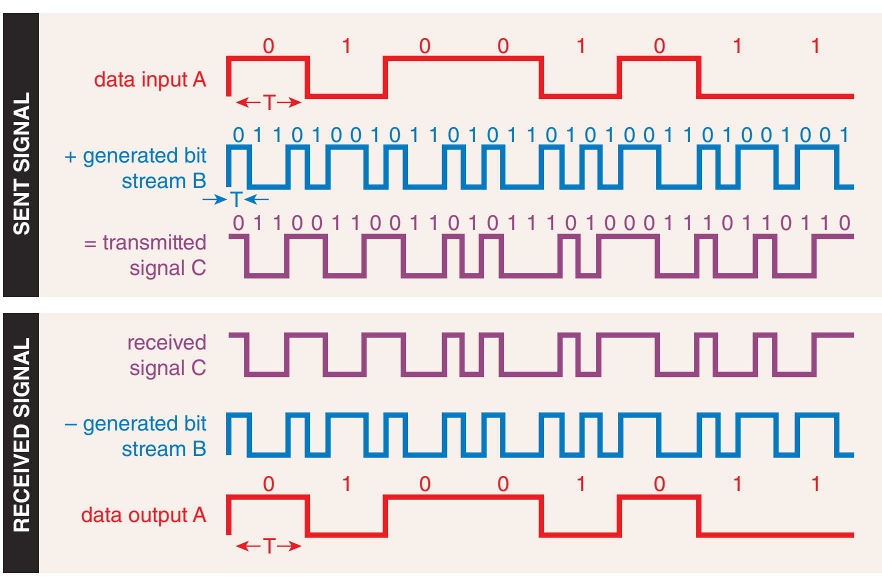
Nor do the antecedents end here. Chaffee was beaten to the punch by another AT&T team, consisting of Otto B. Blackwell, De Loss K. Martin, and Gilbert S. Vernam, whose proposal not only predates all those on Hutchinson's list, but also anticipates many features of the Broertjes and the Lamarr-Antheil inventions as well. On December 18, 1920, the team filed an application for a "Secrecy Communication System," which was finally granted U.S. Patent 1,598,673 on September 7, 1926. The authors write:

> Heretofore in certain types of signaling systems, in which a high frequency wave is utilized as the agency of transmitting the signals, the signals have been transmitted by electromagnetic waves of a definite high frequency or wave length and any station tuned to said wave length might be capable of receiving said signals. In the present invention secrecy is obtained by the transmission of signals on a plurality of waves of different frequencies, successive portions of a message being transmitted on waves of different frequencies whereby a station tuned to one of said waves receives only a partial and therefore unintelligible disclosure of the communication.

The authors go on to say that the frequency shifting is "not accomplished in a cyclic order but rather in a random and variable manner." Anticipating Antheil's player-piano rolls, the team members employ perforated telegraph tape with randomly punched holes to control the frequency hopping. From a technical standpoint, their electronic implementation is superior to the Lamarr-Antheil version in all respects, and is superior to the other Bell Labs patents as well.

## Infinite Regression

At first glance, the patent of Blackwell, Martin, and Vernam appears to nail down the origin of frequency hopping, but the devil lies in the details. Like most of the later Bell Labs inventors, the authors evidently intended to transmit the message across a telephone line after randomly scrambling the audio frequencies to unspecified "higher" carrier frequencies. That approach implies a narrow transmission band. They do state that radio transmission would work equally well, but they do not make clear whether that additional carrier would also hop frequencies. Their patent therefore seems to repre-




**Direct-sequencing is another form of frequency hopping, used in modern cordless phones, Wi-Fi, and the Global Positioning System (GPS). For transmission (*top*), it merges a sent-data input (*A*) with a high data-rate bitstream (*B*) to produce a new signal (*C*) that is highly resistant to both jamming and interference. At the receiving end, the bitstream is removed, or demodulated, to recover the original data input (*bottom*).**

sent audio frequency hopping, but not radio frequency hopping. Interestingly, none of the later patents cite this one or Chaffee's; whether this was the result of a simple oversight or some weightier consideration remains a mystery.

The relative sophistication of the Blackwell, Martin, and Vernam patent compared with its successors demonstrates that technology does not always progress smoothly. It also illuminates the difference between a patent produced by amateurs and one produced by professionals. In 1919, Vernam had patented what has become known as the Vernam Cipher, in which a plaintext message is mixed with a random stream of characters to provide a coded message. It was the electronic implementation of the "one-time pad" (a message key used once and destroyed), which renowned information theorist Claude Shannon of Bell Labs later proved to be unbreakable.

Vernam's 1919 patent (U.S. Patent 1,310,719) is widely considered to be one of the most important in the history of cryptography, so it comes as no surprise that within a year he participated in the invention of a secure transmission system. Later, in one of the most secret projects of World War II, the U.S. military developed Project X, the first uncrackable communications system. It is unclear whether any aspects of the Blackwell, Martin, and Vernam patent influenced the project, but Vernam's ideas on cryptography certainly did.

**The fundamental law of invention is the infinite chain of priority: Someone else always did it first.**

In the Blackwell, Martin, and Vernam patent we see the concept of frequency hopping partly realized, but the endless chain of priority ensures that, yes, the germ of the idea had appeared earlier still. Jonathan Zenneck was an early German radio pioneer who was held during World War I as an enemy alien in the United States, which he happened to be visiting at the war's outbreak. His *Wireless Telegraphy*, the standard textbook on the subject for many years, appeared in Germany in 1909 and in English translation in 1915. In a chapter on receivers, Zenneck discusses varying the wavelength of messages:

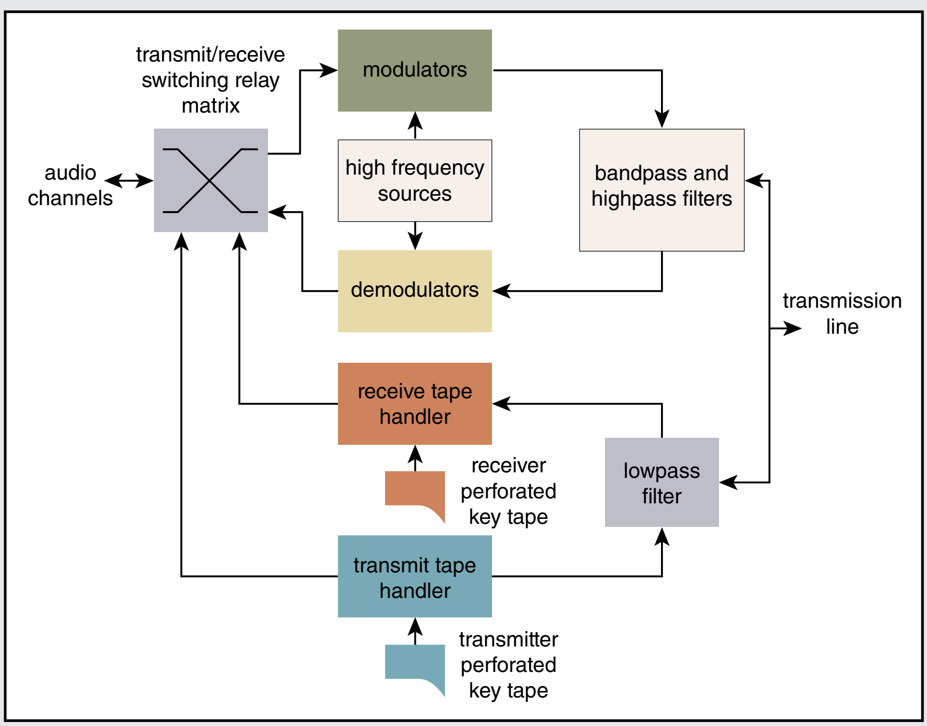
> The interception of messages by stations other than those called, can be prevented to some extent by telegraphing so rapidly that such relays as are customarily used will not respond and only specially trained operators will be able to read the messages in the telephone. Furthermore, the apparatus can be so arranged that the wave-length is easily and rapidly changed and then vary the wave-length in accordance with a prearranged program, perhaps automatically. This method makes it very difficult for an uncalled listener to tune his receiver to the rapid variations, but it is of no avail against untuned, highly sensitive receivers.

Zenneck does not mention that for full secrecy the wavelengths should be shifted in an unpredictable manner, but otherwise the proposal is for frequency hopping in the modern sense. He adds in a footnote that "This method was adapted by the Telefunken Co. at one time," showing that the core principle was applied as early as the opening of the 20th century.

Yet even Zenneck's book is not the technology's *urtext*. Given that Nikola Tesla's obsessive fans have credited him with inventing the radio, the laser, the electron microscope, and the atomic bomb, it would be almost surprising if he hadn't invented frequency hopping,

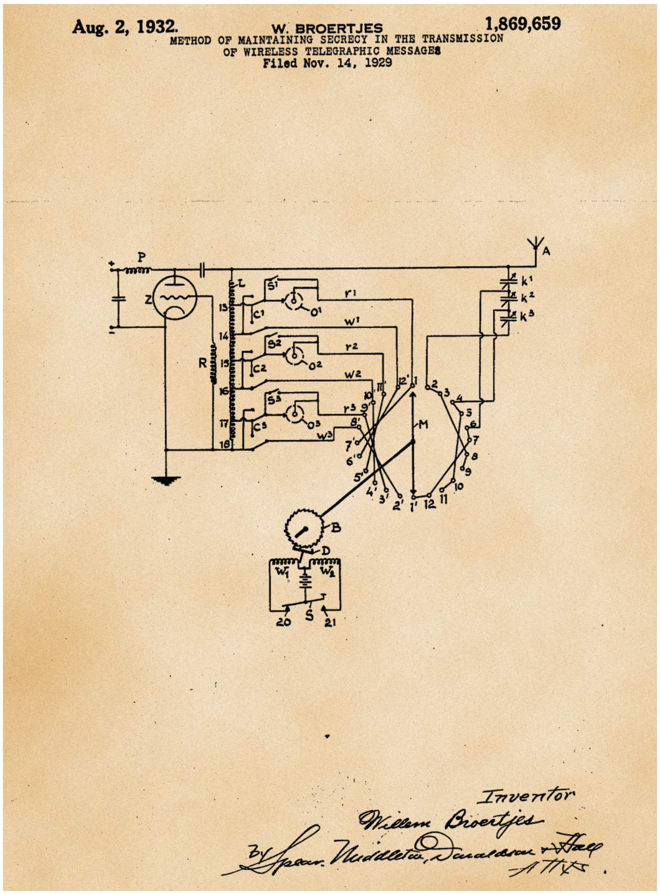
Barbara Aulicino

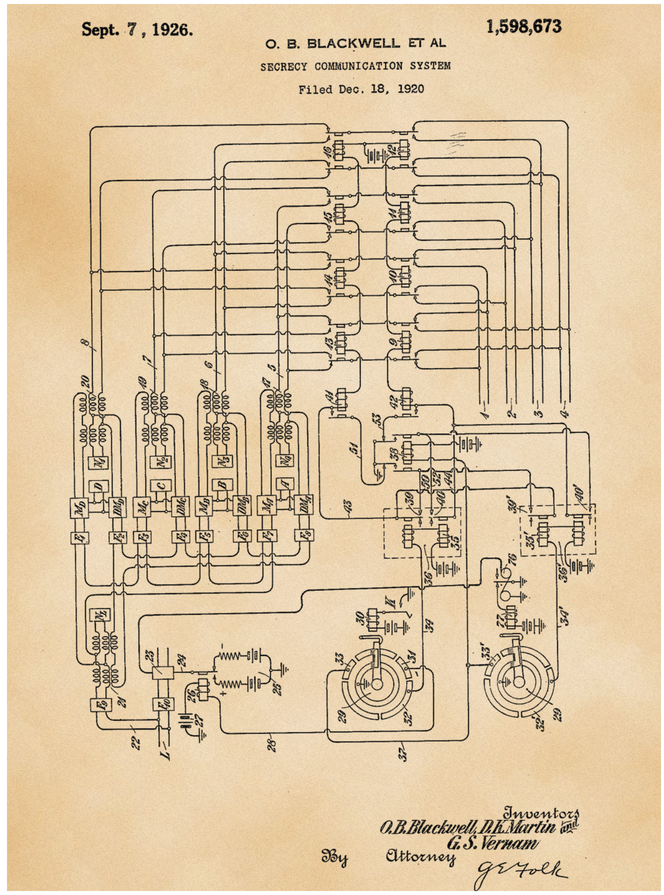
## First Frequency Hopper?




A block diagram illustrates the primary components of the "Secrecy Communication System"—a direct predecessor to frequency hopping—patented by Otto Blackwell, De Loss Martin, and Gilbert Vernam. Audio channels (the original message) are shifted in a pseudorandom sequence to higher frequencies by a switching matrix according to a pattern encoded in a perforated telegraph tape and sent via a tape transmitter. The higher frequencies are combined with carrier frequencies in the modulators; the modulated signals are separated by band-pass filters, then transmitted.

The receiver is basically a mirror image of the transmitter: It demodulates the incoming signals, down-converting them to their original frequencies according to the switching pattern in the telegraph tape, to recover the message.




**Dutch inventor Willem Broertjes described a form of frequency hopping for secure communication in a patent (*left*) filed in 1929, a dozen years before Hedy Lamarr and George Antheil filed. In 1920 American Telephone and Telegraph researchers Otto Blackwell, De Loss Martin, and Gilbert Vernam patented a system (*right*) that anticipated pivotal aspects of later frequency-hopping schemes, including changing frequencies by punching random holes in a telegraph tape.**

U.S. Patent Office

too. Here, Tesla might even have a legitimate claim. In U.S. Patent 723,188 (applied for in 1901, granted in 1903), he considers a "Method of Signaling" that consists of two or more transmitters operating on different frequencies. The receiver is designed to respond only when both signals are received.

Tesla's language is obscure, but his essential idea is the familiar one that by varying the frequencies in a predetermined pattern, only the desired receiver will be able to detect the transmitted message. Here the chain of priority at last fades out, for if one goes much earlier, the concept of radio itself had yet to be born.

### The Randomness of History

No history of invention will ever be complete. In a seminal 1982 article on the history of spread-spectrum communications, electrical engineer Robert Scholtz of the University of Southern California cites several hundred contributions to the technology's development. Nevertheless he overlooked some, including the Lamarr-Antheil patent and the other early patents discussed here. The 1994 *Spread Spectrum Communications Handbook*, by Marvin Simon, Jim Omura, Robert Scholtz, and Barry Levitt, awards Lamarr and Antheil their due prominence but still misses others. At the other extreme, *Bombshell* fails to mention any of Lamarr and Antheil's predecessors.

Any approach to the history of science and technology that aggrandizes lone inventors is largely static: Beyond the snapshots of inspirational eureka moments, nothing much happens. Borrowing a metaphor from biology, we might call this view "extreme punctuated equilibrium." Between disruptive interventions of genius, scientific progress grinds to a halt.

Yet surely in science and technology the protagonists should be the ideas themselves. The essential lessons—and excitement—from the history of science derive from observing the evolution of an idea, from its nebulous birth to the time at which it condenses into recognizable form. Ideas, in a real sense, have a life of their own. In science, if you don't think of something, someone else will, and in nearly the same words, as the frequency-hopping patents amply demonstrate.

If ideas are born of necessity, then the mother of secret communications has been war. Most of the research into spread-spectrum transmission took place in anticipation of war, or during war itself. By some estimates, during World War II as many as 90 percent of German electronics engineers were involved in the country's (ultimately unsuccessful) anti-jamming campaign. Under such circumstances, the invention of frequency hopping was not just probable, it was inevitable.

Tracing the development of a technology such as frequency hopping in an evolutionary fashion is not easy. History begins to vanish the moment a blackboard is erased. In this case, not only were numerous patents overlooked, but much of the work was classified, leaving gaps in the historical record and resulting in repeated, near-duplicate inventions. At about the time Lamarr and Antheil were finalizing their ideas, the U.S. Army Signal Corps commissioned Bell Labs engineers to begin work on Project X, also known by its code name, SIGSALY. Based on the labs' earlier vocoder (voice encoder) system, SIGSALY went online in 1943, ultimately carrying encrypted voice communications between U.S. President Franklin D. Roosevelt and British Prime Minister Winston Churchill.

SIGSALY became the first completely uncrackable secret communications system. It digitized the voices of the interlocutors and then scrambled their amplitudes according to one-time pads, which in this case were vinyl recordings that sampled the randomly fluctuating brightness of mercury-vapor lamps. These vinyls—cousins of Antheil's player-piano rolls—were shipped to Washington and London, where turntables tuned to the National Bureau of Standards timing signal started up at the same instant. After a single use, the vinyls were destroyed.

Because SIGSALY scrambled voice amplitudes rather than frequencies, it was not *de jure* frequency hopping. Then again, because transmission of the radio signals involved frequency modulation, the random amplitudes got scrambled to random frequencies, making it a *de facto* frequency-hopping scheme. To this day SIGSALY is little known to the public, surely because many of its innovations remained classified until 1976.

During the postwar era, another major effort at developing a secure, jam-proof system was put forth by Sylvania with its Buffalo Laboratories Application of Digitally Exact Spectra, or BLADES, which began in 1955 as system for communicating with Polaris submarines. It was tested by 1957 and in 1963 it was installed on the flagship U.S.S. Mount McKinley, where it successfully thwarted intentional jamming efforts. Evidently it was the earliest frequency-hopping system put into action. The details of BLADES are still murky, because it was (and perhaps remains) classified.

The secrecy surrounding BLADES and other military research has bolstered the story that early frequency-hopping systems put into practice after World War II all derived from the Lamarr-Antheil patent. Reality is neither so simple nor so linear. The handful of available patents that provide the basis for BLADES's operation make no mention of the Lamarr-Antheil patent. The ideas prevailed, not the individuals.

**If ideas are born of necessity, then the mother of secret communication has been war.**

### Shadows of Invention

Although the spread-spectrum approach is now ubiquitous in commercial communications, tracking its provenance is no easy task. Bluetooth technology does employ frequency hopping, but its inventor, Jaap Haartsen, tells me that he was unaware of the Lamarr-Antheil patent when he was working on the system at Ericsson in the 1990s. Frequency hopping was merely the standard that the U.S. Federal Communications Commission (FCC) required on the frequency band he intended to use for an interference-proof local communication system.

Many recent articles cite Lamarr-Antheil's invention as having been vital to the development of modern Wi-Fi, but Haartsen also points out that Wi-Fi abandoned frequency hopping early on, because it provided insufficient bandwidth. For a time, Wi-Fi used a spread-spectrum technique known as *direct sequencing*, but since a change in FCC rules, it employs yet another type of spread-spectrum technology, *orthogonal frequency division multiplexing*. The Global Positioning System (GPS), another alleged part of Lamarr's legacy, has always used direct sequencing. Although the early 2G cellular network did use a form of frequency hopping, later networks have employed direct sequencing and orthogonal frequency division multiplexing. Any link to player pianos and torpedoes has yet to be demonstrated.

As with the history of radio, an unofficial form of classification has left its distorting stamp on the history of frequency hopping: nationalism. All of the patents discussed here are German or American, but surely that cannot represent the full reality. During the lifetime of the Soviet Union, Western researchers had little idea of what was going on there, but that hardly means that Soviet scientists were idle. In 1935, a Russian communications engineer named Dmitri Vasilievich Ageev published a paper titled "Principles of the Theory of Linear Selection," which lays down the mathematical basics of spread-spectrum techniques. There may well be other Soviet contributions that have not yet come to light, but we do know that as early as 1957, prototype mobile phones, evidently based on Ageev's ideas, were operational in Moscow.

So long as large swaths of technological research take place under secrecy, redundancy and inefficiency will remain facts of life. As a former National Security Agency employee once remarked to me, "The military usually develops an idea 10 years before the civilian sector." To the extent that the comment was not an idle boast, it does suggest considerable hidden and wasted intellectual resources. Private corporations, too, guard their secrets, fueling duplication of effort, even as cutthroat competition engenders horse-trading that allegedly keeps consumer prices down.

As a rule, scientists engaged in fundamental research would rather do something novel themselves than try to duplicate someone else's results, which only adds to the noise. In that regard, the overwhelming concentration of talent at the old Bell Labs had its advantages. It may be too much to hope that a new system can be devised to streamline the chaos. Failing that, one can at least take solace from knowing that recognition for one's accomplishments depends largely on the diligence of the patent search, and that the march of ideas will continue regardless of who gets the credit.

### Bibliography

Scholtz, R. A. 1982. The origins of spread spectrum communications. *IEEE Communications Transactions* 30:822–854.

Simon, M. K., J. K. Omura, R. A. Scholtz, and B. K. Levitt. 1994. *The Spread Spectrum Communications Handbook.* New York: McGraw-Hill.

Rothman, T. 2003. *Everything's Relative and Other Fables from Science and Technology.* Hoboken, NJ: John Wiley and Sons.

For relevant Web links, consult this issue of *American Scientist Online:*

www.amsci.org/magazine/issues/2018/january-february