Spread Spectrum − Secret Military Technology to 3G

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Abstract: **Guglielmo Marconi probably made the first spread spectrum transmission without even realizing it. His primitive spark-gap transmitter used an RF bandwidth that was much wider than the information bandwidth. Little did he know that his experiment would spark a revolution in communications technology. Today, wireless communications plays an integral part in our daily lives. Cellular phones are quite commonplace and we can hardly imagine life without them. In the future, we would not only use them to have conversations, but to access the internet, watch the latest news updates or even manage our daily schedules – the possibilities are endless. Yet, at the heart of this technological marvel lies an idea that was born 60 years ago, and at that time, was scoffed at as being unrealistic and impossible. This article traces the evolution of spread spectrum technology from the pre-war days till today.**

The beginning:

Strangely enough, spread spectrum, the technology that holds the potential to revolutionize the world of wireless communications, was born in the place you'd least expect – Hollywood. The story goes back to 1941, when, at the peak of the war Hedy Lamarr, called "the most beautiful girl in the world" by some, was a glamorous movie star. Her life story is arguably more alluring, and certainly more heroic, than any role she ever played on the silver screen.

Lamarr came to Hollywood shortly before the war broke out in Europe after escaping from her first husband, Fritz Mandl, who was selling munitions to Hitler. Mandl was conducting research in weapons control systems. At the time studies indicated that radio waves were better than wires for controlling weapons such as torpedoes. For one thing, it was difficult to make a wire that was long enough and for another, there was no guarantee that the wire would not break. Radio waves solved the problem by not requiring any physical connection between the commander and the torpedo. But, they had a serious flaw: enemies could access the same radio channel and jam it.

As Mandl's wife, Lamarr was exposed to military technology. Mandl kept her at his side during his business meetings, a silent witness to the technical discussions that foreshadowed World War II. Although she had no formal education in military technology, she had a mind capable of understanding what she heard. After four years in a bad marriage to Mandl, Lamarr drugged her maid and left him forever.

George Antheil had been at the forefront of experimental music in the 1920s. He was quite famous in Europe and in the early 1930s, received a Guggenheim fellowship to go to Europe. But when Hitler began to close the German opera houses that presented modern music, Antheil returned to the U.S. He always felt that he had to leave Europe because of Hitler and emphatically opposed the Nazis.

They met each other at a party in Hollywood and became friends. During the course of their conversations, which usually centered on the war and how something ought to be done about it, Lamarr told Antheil about her idea of a Secret Communications System that could guide torpedoes to their target without being intercepted by the enemy, by sending messages over multiple radio frequencies in a random pattern. The message would move so quickly across frequencies that anyone listening in on a particular frequency would only hear a blip and would be unable to decipher the message. The only problem was how to synchronize the transmitter and the receiver.

As a result of his experiments in music, Antheil had come across a solution for the invention to work – two paper rolls with the same pseudo-random sequence perforated on them would demarcate the choice of frequencies. If the two rolls were started at the same time and the motors had a good rotary stability, synchronization could be maintained right to the point the torpedo hit its target. Their original design used 88 frequencies, corresponding to the number of the keys on the piano and was the world's first Frequency Hopped Spread Spectrum (FHSS) System [1].

On 11th August 1942, Lamarr and Antheil were awarded U.S. Patent number 2,292,387 for their Secret Communications System. Despite the fact that they stood to gain financially from the patent, they gave it to the government as part of the war effort. The Navy however refused to take their invention seriously. They were filled with skepticism about whether the rolls would be accurate enough or whether they would break, and the fact that Antheil had explained several of his ideas with the analogy to the player piano (an automated musical instrument), didn't help either.

When the war ended, Lamarr and Antheil put their invention behind them. Antheil was not to see his idea come to fruition during his lifetime.

Fig1: Hedy Lamarr (left) – "The Most Beautiful Girl In the World" and George Antheil (right) – "The Bad Boy of Music" – co-inventors of Spread Spectrum

The early years:

As the years progressed, so did electronics technologies and in the 50s, engineers from Sylvania Electronics began to experiment with the ideas in the Secret Communications Systems patent, using digital components instead of paper rolls. They developed an electronic spread spectrum communications system that handled all secure communication for the U.S. during the Cuban missile crisis of 1962.

The term "spread spectrum" first came into use in the early 1960s. Today, it refers to radio communications systems that employ cryptographic subsystems, use a wide frequency spreading factor and do not employ any particular type of tonality in the transmitted waveform [2]. Lamarr and Antheil's system was the first to satisfy all three criteria.

Spread spectrum (SS) was a particular favorite with the military because of its low probability of interception, which means that it is difficult for eavesdroppers to listen in. It also has anti-jamming capabilities, which means that unauthorized sources cannot transmit false information to mislead or spoof the receiver.

Most of the work done on spread spectrum during the '50s '60s and '70s was heavily backed by the military and shrouded in secrecy. It has only been recently declassified. These include secure communication sets, radar, satellite communications and even the Global Positioning System (GPS), which is the world's single largest spread spectrum system.

Technology opens up:

Through his revolutionary paper in 1948, "A Mathematical Theory of Communications," Shannon gave us a relationship defining the amount of information that can be sent down a noisy channel using a given transmit power and bandwidth. In defining how much information can be sent through a noisy channel, Shannon showed that engineers could choose between narrow-band high-powered solutions or broadband low powered ones.

Traditionally the FCC had favored narrow-band radios, which concentrate all of their power in a narrow portion of the radio frequency spectrum [3]. However, as the number of users increased, the number of available channels was used up. Also, as a result of their very narrow frequency band, these radios were prone to interference (a single interfering signal at or near their frequency can easily render the radio inoperable).

As if anticipating this predicament, Shannon offered a new paradigm, redefining the relationship of power, noise and information. Shannon said that a signal conveys information to the extent that it provides unexpected data. He called the information content of a signal "entropy." In digital communications, another name for a stream of unexpected bits is random noise. Shannon showed that the more a transmission resembles this form of noise, the more information it can hold, as long as it is modulated to a regular carrier frequency. In the esoteric language of Shannon, one needs a low entropy carrier to bear a high entropy message [4]. Hence, according to Shannon, an alternate to transmitting a signal with a high power and low bandwidth would be to use a low power and a wide bandwidth.

Spread spectrum is a technique that takes a narrow band radio signal and spreads it over a broader portion of the radio frequency spectrum. This has the operational advantage of being resistant to interference. However, due to the concerns of the increased frequency space that it occupies the FCC until recently did not permit commercial use of the technology.

However, in 1985, catalyzed by the continuing evolution of digital technology the FCC recognized the performance and operational advantages of spread spectrum data radios to end users and amended its regulations to open up three spectrum bands for unlicensed commercial operation. Today, these are the Industrial Scientific and Medicine (ISM) bands, which cover 902 to 908 Mhz and 2400 to 2483.5 MHz, and the Unlicensed National Information Infrastructure (UNII) band from 5752.5 to 5850 MHz. The FCC allows the use of these bands for unlicensed commercial operation provided the transmission power is less than 1 Watt, so as to prevent interference in the band over long distances [5]. These bands are also used by the IEEE 802.11 series of Wireless LAN standards.

So, What is Spread Spectrum?

Perhaps, this is a good point to digress from the history of spread spectrum to discuss the How's and Why's of Spread Spectrum.

One way to look at spread spectrum is that it trades a wider signal bandwidth for a better signal to noise ratio. The two main types of spread spectrum systems in use today are Frequency Hopped Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). The following paragraphs will describe each of these common techniques in a little more detail and show that pseudo-noise techniques provide a common thread through all spread spectrum types [2 & 6].

Direct sequence spread spectrum systems are so called because they use a locally generated pseudo-noise code or sequence to encode the digital data to be transmitted. Data for transmission is simply modulo-2 added or XORed with the faster pseudo noise sequence (see Figure 2). This combination of the data and the high speed PN sequence is then used to directly modulate an RF carrier. The ratio of the code rate to the information rate determines the extent of spreading and is also called the processing gain. Typical systems use processing gains ranging from 20 to 254, although gains as high as 1000 have been used. The periodicity of the PN code sequences can be as low as 11 bits or as high as [2^{89}-1] bits. DSSS is one of the most practical spread spectrum systems around because of its all-digital nature.

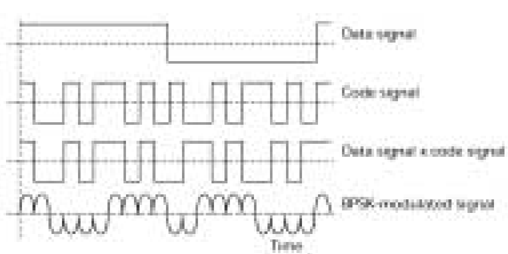

Fig 2: Generation of a DSSS Signal

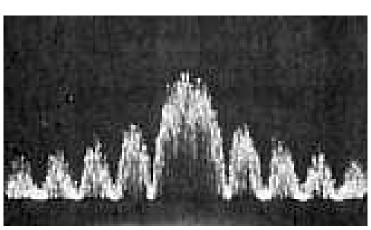

Fig 3: Spectrum of a DSSS Signal

An SS receiver uses a locally generated replica pseudo noise code and a receiver correlator to separate only the desired coded information from all possible signals. An SS correlator can be thought of as a very special matched filter – it responds only to signals that are encoded with a pseudo noise code that matches its own code. Thus, an SS correlator can be "tuned" to different codes simply by changing its local code. Thus, the correlator does not respond to man made, natural or artificial noise or interference. It responds only to SS signals with identical matched signal characteristics and encoded with the identical pseudo noise code.

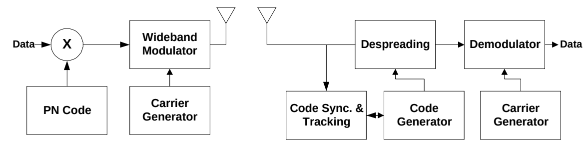

Fig 4: Block Diagram of a DSSS Transmitter and Receiver

Frequency hopping is the easiest spread spectrum modulation to use. The wideband frequency spectrum (see Figure 5) desired is generated in a different manner in a frequency hopping system. It does just what its name implies. That is, it "hops" from frequency to frequency over a wide band. The specific order in which frequencies are occupied is a function of a code sequence, and the rate of hopping from one frequency to another is a function of the information rate.

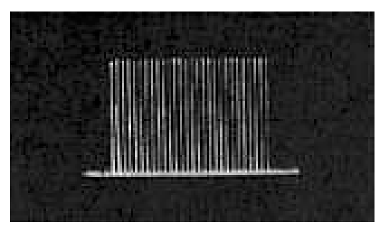

Fig 5: Spectrum of a FHSS Signal

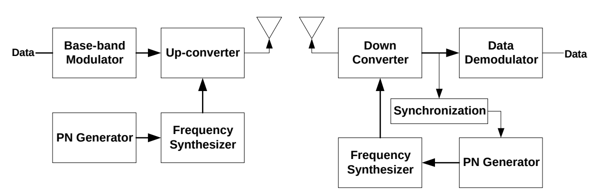

Fig 6: Block Diagram of a FHSS Transmitter and Receiver

Theoretically, any radio with a digitally controlled frequency synthesizer can be converted into a frequency-hopped radio. All that is needed is to add a PN code generator to select the frequencies for transmission or reception. De-hopping in the receiver is done by a synchronized pseudo noise code generator that drives the receiver's local oscillator frequency synthesizer (see Figure 6).

The use of these special pseudo noise codes in spread spectrum communications makes signals appear wide-band and noise-like. It is this very characteristic that makes SS signals possess the quality of Low Probability of Intercept. SS signals are hard to detect on narrow band equipment because the signal's energy is spread over a bandwidth of maybe 100 times the information bandwidth.

The spread of energy over a wide band, or lower power spectral density, makes SS signals less likely to interfere with narrowband communications. Narrow band communications, conversely, cause little to no interference to SS systems because the correlation receiver effectively integrates over a very wide bandwidth to recover an SS signal. The correlator hence “spreads” out a narrow band interferer over the receiver’s total detection bandwidth. Since the total integrated signal density or SNR at the correlator's input determines whether there will be interference or not, an SS receiver is immune to narrow band interference. All SS systems have a threshold or tolerance level of interference beyond which useful communication ceases. This tolerance or threshold is related to the SS processing gain.

Spread Spectrum today:

Up until 1999, when its shares rose in value by 2619 percent, making it the leading star of the globe’s stock markets, few people had heard of a company in San Diego, called Qualcomm. Qualcomm could defy the world and prevail because it listened to technology, while its rivals listened to their customers and their experts. Like the computer industry before it, cellular providers were still ambivalent towards new vectors of technology. They were happy using the then current state of the art in cellular technology, namely Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) and believed that Irwin Jacobs and Andrew Viterbi’s new system Code Division Multiple Access (CDMA), which is based on direct sequence spread spectrum, could do no better [4].

However, with studies indicating that CDMA based systems can have capacities ranging from 6 to 10 times those of their TDMA or FDMA counterparts, today CDMA has taken the world by storm. Even the Europeans, who were once staunch proponents of its rival technology Time Division Multiple Access (TDMA) have accepted CDMA as the air interface for their 3rd Generation standard, Wideband CDMA.

Apart from its application to cellular telephony, spread spectrum technology is employed in a number of other diverse areas. For instance the Navstar Global Positioning System (GPS) that was once a classified air-force project is now being used for civilian applications. This constellation of 24 US Department of Defense satellites orbit the earth at 20,200 km. in 6 different orbital planes, circling the earth once every 12 hours. They transmit a spread spectrum signal containing information about the satellite number, it’s orbital position and clock information. With four satellites in view, a receiver on earth can correlate each of the received signals to acquire this data and calculate its position on earth based on their time of arrival [7].

Although the current positional accuracy on the civilian system is 100 m, while military users enjoy an accuracy of 1 m, GPS is finding its way into a number of applications ranging from navigating ships to helping hikers find their way to making sure that ambulances get to an emergency victim on time.

Another “hot application” for spread spectrum technology is in Wireless LANs. These were originally envisioned to have applications in buildings where the costs of installing and maintaining a wired LAN were prohibitive, such as historic buildings and in places where the operational environments may not accommodate a wired LAN, or the network is only temporary. Examples of these include conference registration centers, classrooms, emergency relief centers and tactical military environments.

With these goals in mind, in 1997, after seven years in the standardization process, the IEEE standards committee announced the IEEE 802.11 standards that operate using a choice of DSSS or FHSS in the 2.4 GHz ISM band with a bit rate of 1 or 2 Mbps. The initial standards were so popular that close at it’s heels came the IEEE 802.11b and IEEE 802.11a standards that support bit rates of 11 Mbps and 55 Mbps respectively. Most WLAN implementations today are IEEE 802.11b compliant and products supporting the higher bit rate 802.11a are scheduled to be on the market towards end 2001 [8].

Today, WLANs are found in several university campuses, opening up new vistas in interactive learning. They are also widely used in industrial environments such as shop floors or even in the corporate board room to enable ready access to the plethora of information that we need to deal with almost everyday.

The future:

3G is slated to hit international markets in 2001 and with it come promises that will revolutionize the way we perform the most mundane of everyday tasks…

Like any other day, Jim is driving to work, listening to his voicemail on his cellular phone. Using a Bluetooth (an SS technology that aims to serve as cable replacement for small everyday devices) link to his cellular phone, his car computer informs him of a rise in engine temperature and an imminent breakdown. With a built in GPS locator the phone determines the nearest service station and downloads a map to get there. It also faxes the station ahead of time informing them that they are coming in. Meanwhile, the phone books a cab from the station to Jim's office and automatically reschedules Jim's appointments to take into account the unexpected delay due to his car breakdown.

Of course, the scenario described above would not be possible without the convergence of several other technologies such as the internet and micro-computers, but, a very crucial ingredient to this would be spread-spectrum technology that would enable the GPS device and the wireless communications links. The possibilities and the applications are endless – one is only limited by one's imagination.

Spread spectrum is once again in a position of potentially making a tremendous contribution to the public good. It's not exactly what Lamarr and Antheil had in mind when they invented their Secret Communications System, but it is something that will certainly revolutionize the way we live. And, it has only taken us 60 years to realize that the unlikely collaboration of a celebrated movie star and an avant-garde composer could possibly invent a communications technology that is still at the forefront today.

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