Signaling Processes in Third Generation Wireless Systems

Abstract

The laws of Nyquist and Shannon govern the world of data communications—the information carrying capacity of a channel is a function of the channel's bandwidth and noise. In wired networks, we have developed ways to reduce noise and increase the channel's bandwidth. In many respects, the bounded media of the wired world has almost boundless channel capacity. However, in wireless communications the properties of the channel are not as easily manipulated. Ironically, this seemingly unbounded medium of the airwaves has some severe limitations. As we move toward the information capacity required for 3G wireless communications, we need to develop signaling processes that allow high data rates in relatively small channels. Some people call these procedures post-Shannon architectures. This paper examines such architectures.

We first examine the techniques known as signal hardening, signal shaping, and signal reconstruction or recovery. Then we look at processes that deliberately spread the signal, for example, direct sequence spread spectrum (used in the CDMA systems) and orthogonal frequency division multiplexing. All of these procedures take a different view of the laws of Nyquist and Shannon. Post-Shannon architectures are being deployed today, as are other potential signaling solutions, for third generation (3G) wireless systems.

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Introduction

George Calhoun, in his book, *Third Generation Wireless Systems, Volume 1 Post-Shannon Architectures*, presents an interesting discussion of the work of Claude Shannon as it relates to wireless communications. He discusses several signaling processes that move the theories of Shannon into the world of 3G wireless communications—a world that Calhoun refers to as "post-Shannon." This paper presents an overview of the topics, and hopefully piques your interest enough to pursue the topics further.

The Need for Speed

There is much debate over the deployment of 3G wireless systems. In fact, several schools of thought believe 3G cellular wireless systems will not be needed because of the popularity of wireless LAN systems such as Wi-Fi. For our purposes this argument is moot since both 3G cellular and Wi-Fi use similar signaling techniques. Regardless of your stance on 3G versus Wi-Fi, a quick analysis of current voice usage trends coupled with a look at potential data uses proves that additional capacity will be needed in either system.

Usage figures from just the cellular perspective show that we will need increased capacity for both voice and data. Moreover, if data is to be successful the transmission quality must improve. The acceptable bit error rate for voice could lead to a significant number of data retransmissions and an unacceptable throughput. The challenge is to take the available spectrum and increase the information carrying capacity.

The World According to Claude Shannon

In 1948, Claude Shannon authored his famous paper, “A Mathematical Theory of Communications,” and established himself as the creator of digital communications. His paper was the result of research on how fast the telegraph could operate. Calhoun includes a short biography of the man and references to more complete biographies.

Before exploring Shannon’s work, we must examine Harry Nyquist’s work, which he presented in his 1928 paper, “Certain Topics in Telegraph Transmission Theory.” Nyquist observed that a channel’s signaling rate was a function of the channel’s bandwidth. Moreover, he proved that the signaling rate must be twice the bandwidth of the signal being transmitted. The Nyquist rate for a 3000 Hz voice channel would be 6000 samples per second. As students of digital telephony know, the actual rate used is 8000 samples per second, which allows for two guard bands, one on either side of the channel. Nyquist also explored signal spacing and signal shaping, but he never looked at how interference affected the signals.

Shannon expanded the work of Nyquist to include interference, or noise. (We will discuss the difference between noise and interference later in the paper.) He postulated that the goal of a communications system was to get the signal through the noise to the receiver. Noise is random, variable, and unpredictable, whereas distortion is not. Distortion can be measured and the channel conditioned to mitigate distortion’s adverse effects.

At the core of Shannon’s work is the equation for a channel’s information carrying capacity:

$$C = W \log (1 + P/N)$$

C is the capacity of the channel, W is the bandwidth, P is the power level, and N is the noise level. An S often replaces the P designation and the resulting fraction, S/N, is the channel’s signal-to-noise ratio. The equation states that the balance between the power and the bandwidth drives the channel capacity. For example, increasing the bandwidth allows us to decrease the power while maintaining the same capacity. The power/bandwidth tradeoff is an important part of wireless communications. Shannon also explored the effects of source compression and channel coding (error detection/correction codes) on information carrying capacity.

From the 1950s through the 1970s, Shannon’s theorem was viewed as an engineering limit rather than an information carrying philosophy. In the 1980s, when we moved to digital wireless to deal with the lack of cellular capacity, Shannon’s work became the reality of wireless communications. In 2003, Calhoun introduces the notion of “post Shannon” to categorize the relevance of Shannon’s work to the capacity-challenged and difficult-to-manage wireless channels. Moreover, this new look at Shannon’s work raises questions about the basic theory. For example, noise addition has proven to be beneficial in some environments.

Designing the Communications Link

To understand the implications of post Shannon topics, you must understand the three design constraints that wireless communications engineers must overcome that are not present in wired systems.

- The physical channel is completely non-engineerable.
- The channel is non-clonable.
- The signal will experience significant, destructive interactions with itself and others.

From an engineer's perspective, the transmitter and receiver are intelligent are separated in space and time. The signal is sent over the channel and influenced by noise—a channel property usually best described statistically. Moreover, the engineer can modify the transmitter, receiver, and channel to improve the communication.

Shannon worked on procedures to encode the information as well as the bandwidth and noise impacts. However, with the advances in wired systems engineering, the coding discussions never surfaced. Wireless channels on the other hand cannot be engineered—they are what they are. In the Shannon world, the *channel* was engineered. In the post-Shannon world, the *signal* is engineered.

The issue of cloning channels in wired systems is quite simple. If you need more telephone hookups, you install more twisted pair or optical fiber. A wireless channel, however, is finite and cannot be replicated. Thus the solution is to share the channel to increase capacity. This leads to issues of medium access control and whether that control is centralized or distributed. These are not insurmountable problems, and they add to the complexity of the wireless system.

The final point is that of interference. Interference is a communications disturbance as opposed to noise, which is a property of the channel. Since everything radiates energy, interference is common. In telephony, the problem of crosstalk is an example of interference—twisted pair helps reduce this interference. In wireless, the communications interfere with themselves. The challenge is not only to deal with the noise, but also with the interference. This is our first glimpse of the idea that noise and interference are different and might need to be treated differently.

Dissecting the Communications System

It is useful to discuss a complex system such as wireless communications according to its components. Calhoun uses a four-level structure in his text.

From a design perspective, the first level of a communications system deals with the channel, signal, and noise. To explain how these work, Shannon created a space, time, and frequency model. Space is the location, or cell, where the transmitter/receiver is located; frequency is the channel being used for the transmission; and time is how the signal progresses (e.g., in FDMA time is continuous because the user has exclusive use of the channel, but in TDMA, time is discontinuous because of the unique time slots allocated for each user to share the channel).

Interference can also be placed in the space, time, and frequency model. In the frequency dimension, using closely spaced channels causes interference called adjacent channel interference. (See Figure 1.) Space dimension interference occurs when the same channel is used in a neighboring cell—called co-channel interference. (See Figure 2.) Time dimension interference occurs when a time slot spills over into another time slot or when one transmitted code, or symbol, interferes with another—called inter-symbol interference.

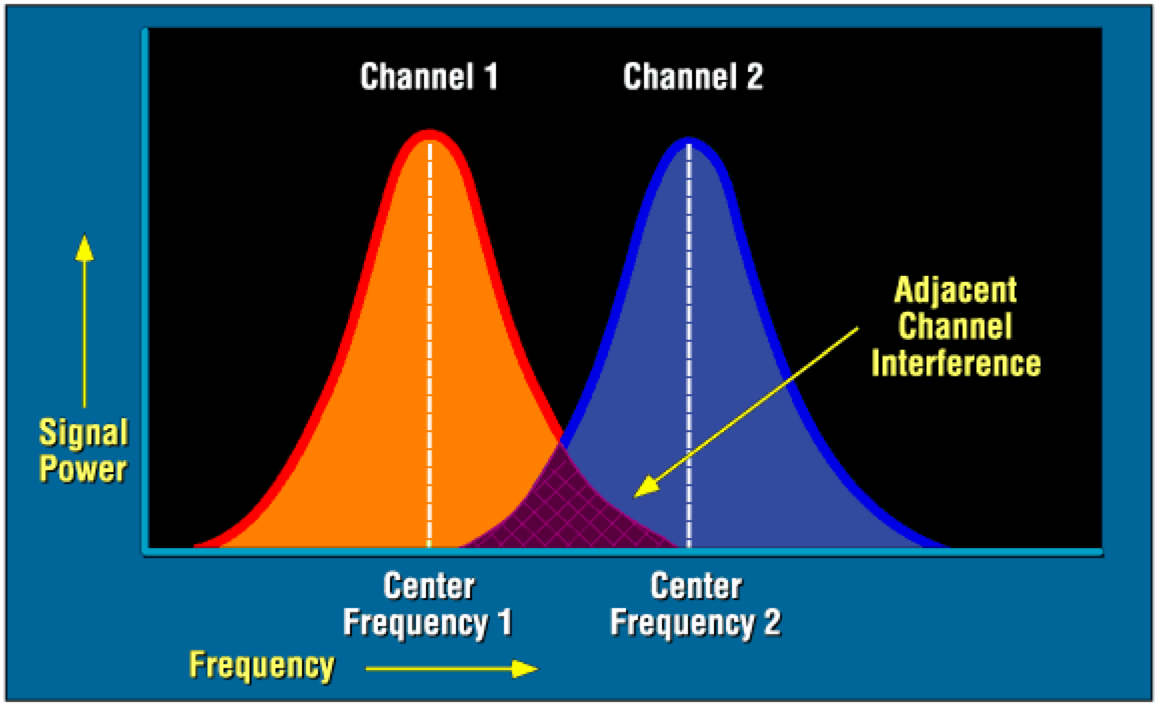

Figure 1: Adjacent Channel Interference

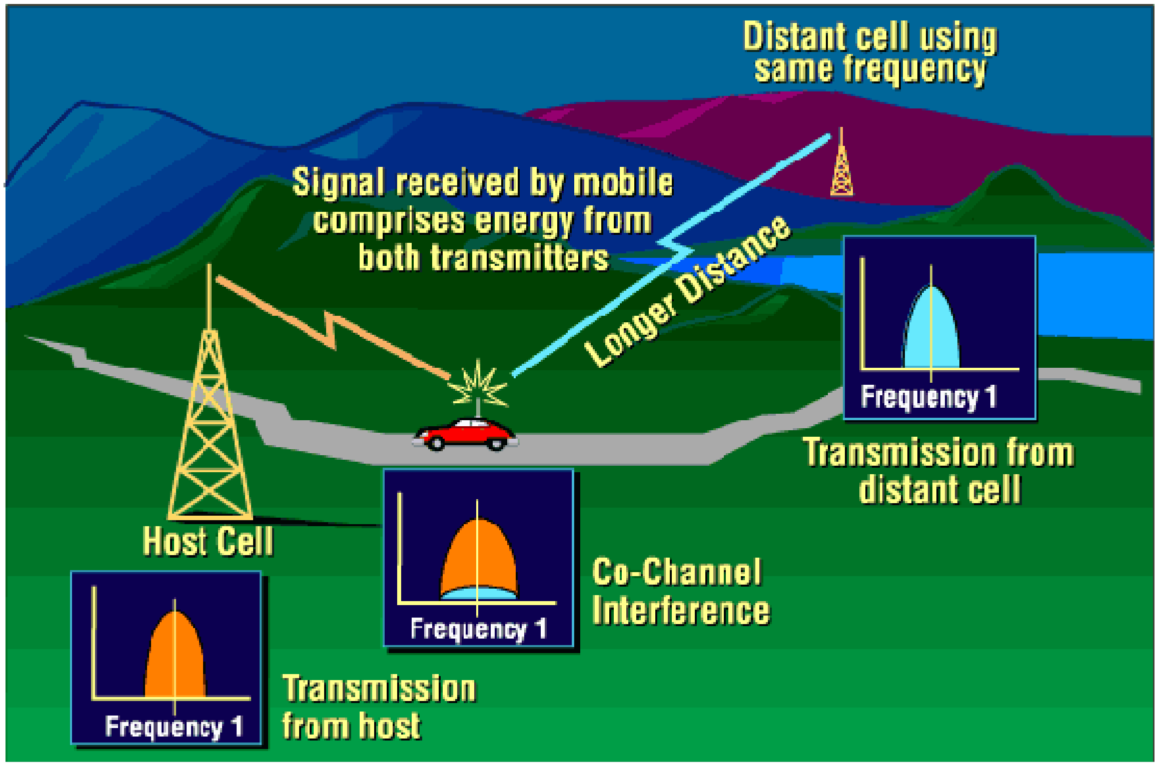

Figure 2: Co-Channel Interference

The limiting factor in wireless communications is not noise, but interference. The more users, the more interference. The closer the spacing, the more interference. And on it goes until the inference drowns out the communication itself. Moreover, self-interference from multipath propagation compounds the problem. (See Figure 3.) In short, wireless communication systems have a variable signal-to-noise ratio, a variable bit error rate, and a variable signal quality.

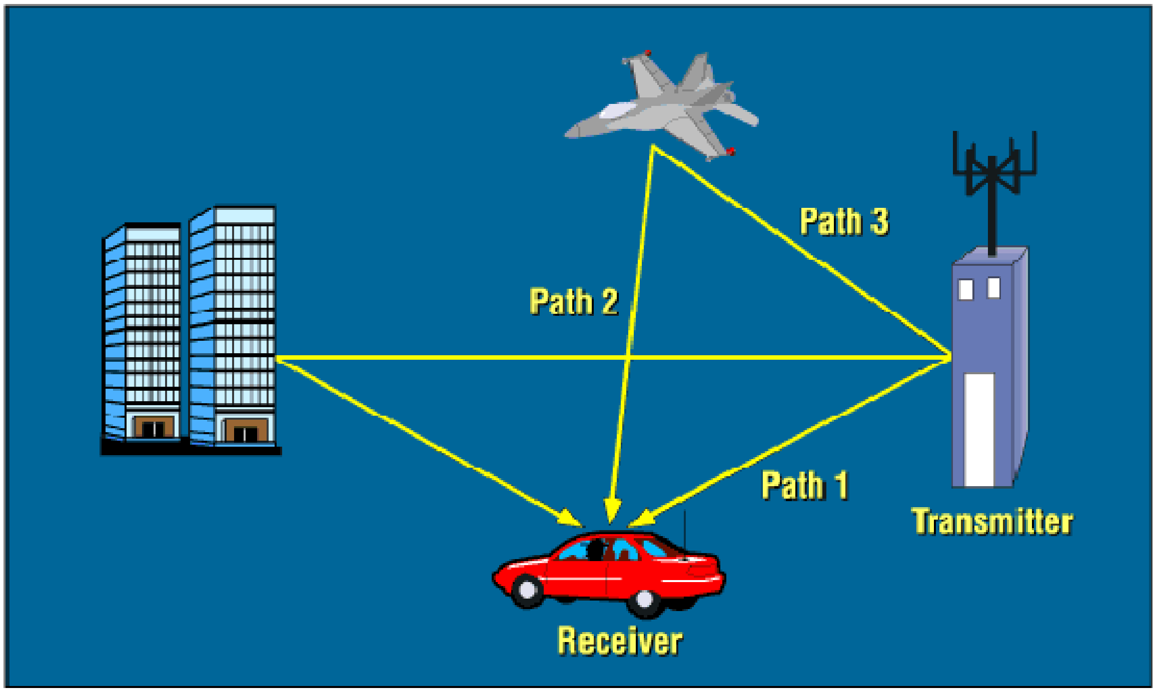

Figure 3: Multipath Interference

The earliest solution to these problems was to ensure that each signal fit in its own little box with plenty of room to spare. In this box, the signal was protected from outside interference by design, an architecture known as orthogonal. The TV world creates orthogonality by assigning every other channel in a particular broadcast area—an expensive solution in terms of lost capacity.

Space, time, and frequency at level one tell us where to look for the signal. At the second level of a communications system, signal amplitude and phase tell us how to read the raw data code. In the world of analog we use amplitude modulation (AM) and frequency modulation (FM). In the digital world we use quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM). (See Figure 4.) Both procedures are widely used in high-speed data communications in the wired world.

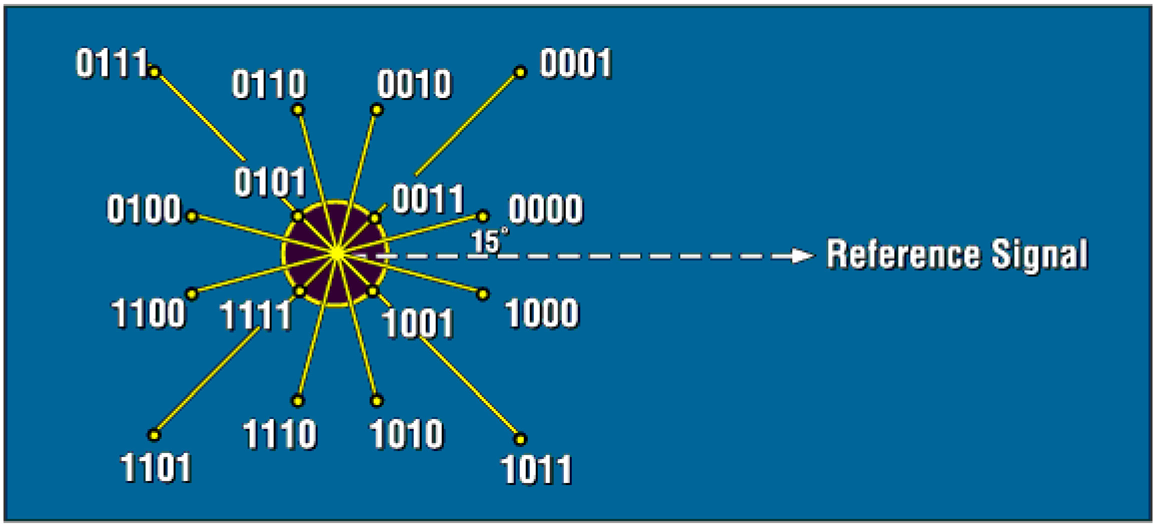

Figure 4: Quadrature Amplitude Modulation

The third level deals with the practical requirements of moving the information. There must be a synchronization procedure between the transmitter and receiver plus an error detection/correction process for the receiver. Add to this things such as pilot signals for quality control, power signals for power control, training sequences for symbol identification, and a hopping sequence for frequency changes and you get a very complex structure at the third level.

At the fourth level, we must define the payload and other functions that might be required to ensure end-to-end message delivery. The OSI Reference Model is an excellent example of how all of the pieces are put together in multilevel communications architectures. (See Figure 5.)

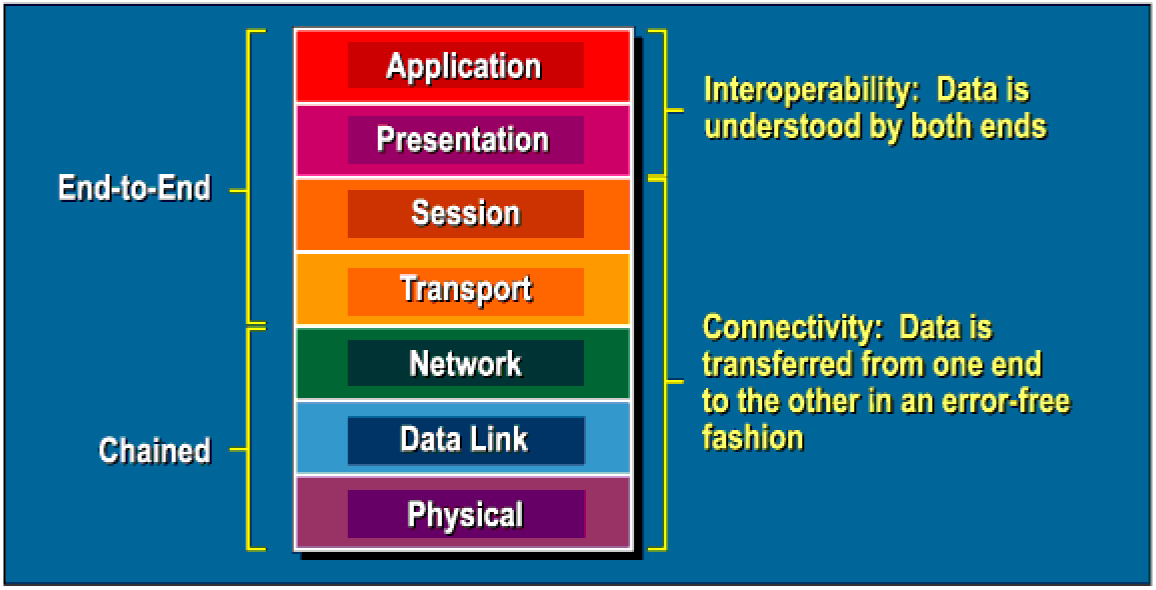

Figure 5: OSI Model Summary

From an historical perspective, the large cells of the early days of mobile communications used more power to overcome noise and expand the coverage area. Unfortunately, this scheme created very little user capacity. The cellular architecture reorganized the space dimension into small, lowpowered cells that provided similar coverage with more capacity and less interference. (See Figure 6.) Second generation cellular used digital methods to reorganize the time dimension, and once again capacity increased. In third generation systems, and in some of the 2G systems, the notion of assigning one signal per cell, frequency, or timeslot is being challenged. The requirement of orthogonality is also being questioned since some systems can productively use interference. Moreover, systems are being designed to work with more interference.

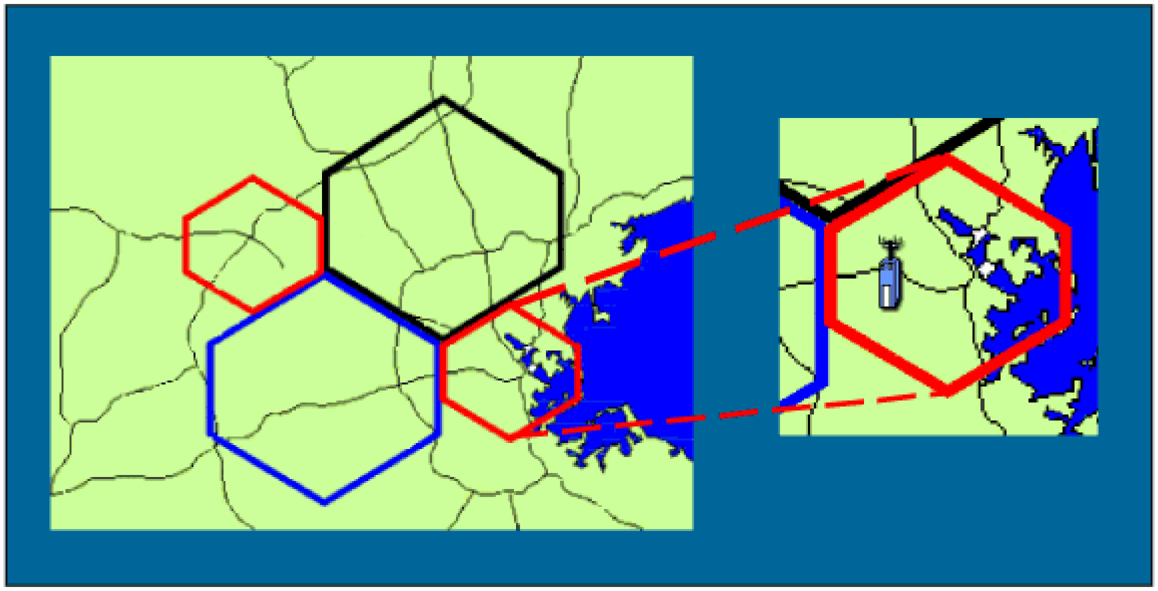

Figure 6: Cell Concept

Post-Shannon Processes for 3G Systems: Orthogonal

In the Shannon world, orthogonality reigned. This meant a philosophy of interference avoidance, buffering in all dimensions, and several capacity problems. In the space dimension, cell patterns and frequency reuse distances limit capacity. (See Figure 7.) In the frequency dimension guard bands and unoccupied channels limit capacity. In the time dimension ramp times, variable propagation delays between time slots, and synchronization issues limit capacity. With all of the problems associated with interference avoidance, perhaps a better solution is to design the interference itself. While controversial, this approach is gaining support as a non-orthogonal solution.

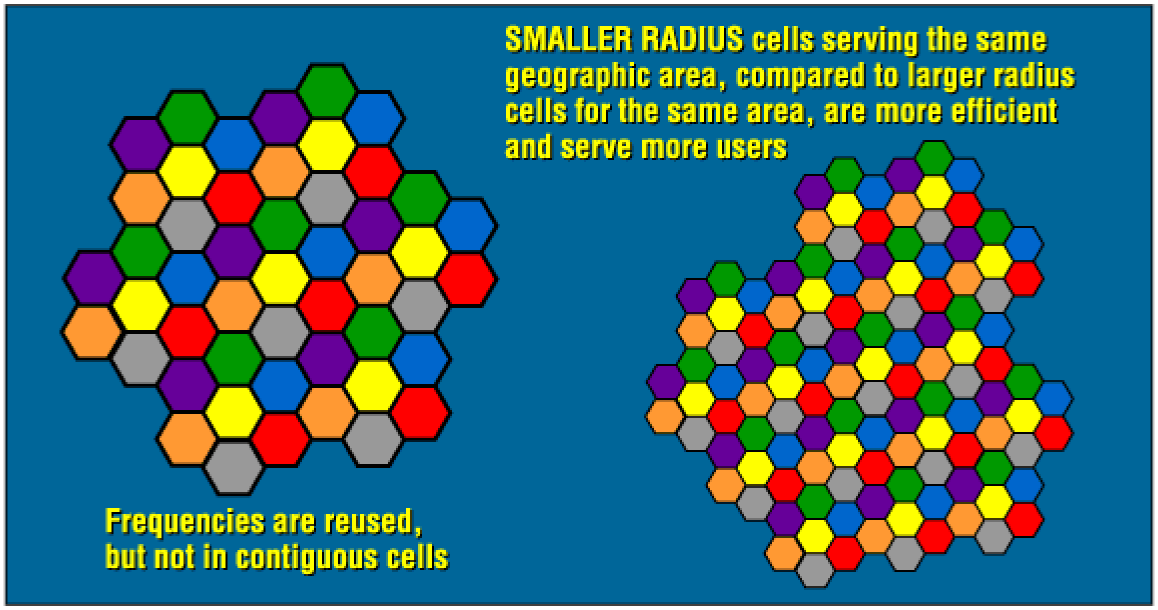

Figure 7: Radius of Cells and Frequency Reuse

Whether we use a non-orthogonal solution or not, there are three ways to deal with interference from the signal perspective.

- Signal hardening: Increase the signal's resistance to interference.
- Signal shaping: Create less interference per signal.
- Signal recovery: Clean up and restore the signal at the receiver.

Signal Hardening

The orthogonal architecture is based on the notion that there is a signal-to- interference ratio threshold below which the receiver cannot discern the signal. Once the threshold level is defined, the buffer requirements can be determined. Signal hardening uses channel coding, diversity, and convolutional codes to increase the signal's resistance to interference.

Channel coding and convolutional coding are very similar in that the information transmitted has additional bits that allow the receiver to detect and correct errors. The most promising of the channel codes are the turbo codes. Some of these have allowed transmissions to approach the Shannon limit on channel capacity. Convolution coders weave the input signals together to create a very robust output signal for transmission. Trellis codes are one of the many convolutional codes.

Diversity is perhaps the most complex of the signal hardening techniques in that it can be used in the space, frequency, and time dimensions. In the space dimension there are multiple antennas; the one with the best signal is used for transmission. This approach eliminates problems associated with holes in coverage. In frequency dimension, the approach is similar except that it uses the best frequency from the range of available frequencies. Fast frequency hopping changes the user's transmission frequency so that only a small amount of time is spent using a non-ideal frequency. Time dimension signal hardening is very similar to the frequency case except now the time slot sampling is optimized.

Signal Shaping

Signal hardening only goes so far as a protection mechanism. An incredibly large amount of interference or an unanticipated error pattern can wreak havoc with the signal. In signal shaping the philosophy is to keep a low profile—interference can't destroy what it can't see. Compression, baseband shaping, spectrum shaping, and beam forming are common signal shaping techniques.

Compression or source coding is also a part of the Shannon discourse on information transport. The idea is to reduce the redundancy in the signal thereby creating a lower profile (i.e., less information to transmit). Baseband shaping and spectrum shaping are very similar in nature. In the baseband case, the transmitter shapes the pulse so that even with interference the receiver can recognize the pulse. The spectrum shaping process shapes the transmitter's energy emission stack so that it does not create additional interference on other channels.

Beam forming, or smart antennas, is a very different approach to signal shaping. In this case the antenna puts the signal where the receiver is located and nowhere else. (See Figure 8.) This not only provides for a shaped signal, but it also reduces the amount of interference created by the signal.

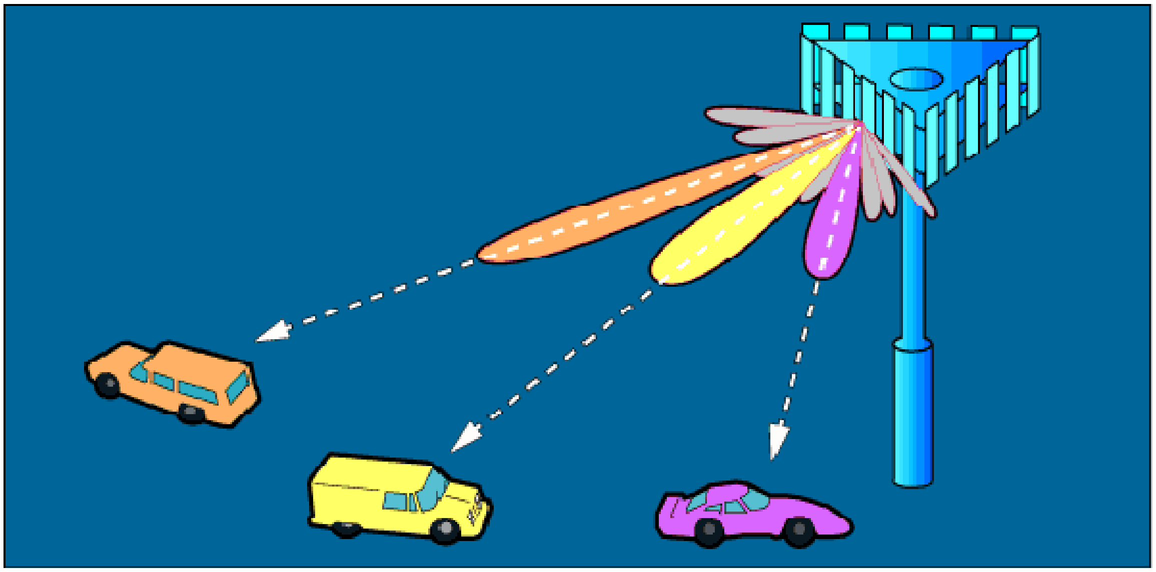

Figure 8: Beam Forming

Signal Recovery

Signal recovery can deal with time and space dimension interference. In the time dimension the techniques include equalization and multipath signal combining. The space dimension relies on spatially selective receivers.

Equalization deals with inter-symbol interference by sending the receiver a training sequence. The transmitted sequence is a known pattern. By comparing the received sequence with the known pattern, the receiver can determine the effects of interference on the signal and make the necessary adjustments to decode the transmitted information. This technique is used in contemporary dial-up modems to determine the appropriate operating speed.

Multipath combining is used in spread spectrum systems. The process combines all of the signals, primary and delayed, to create the final signal. Spatially selective receivers use a process in which the antennas steer the transmission beam to the receiver. This recovery mechanism is a smart antenna solution.

Post-Shannon Processes for 3G Systems: Non-Orthogonal

In the previous section, we looked at a set of processes that beefed up the orthogonality of the systems. These techniques did not constructively use the interference in the system—they just attempted to limit the interference's adverse effects. Here, we examine solutions that go beyond just orthogonality. In fact, these systems are not orthogonal architectures.

First, though, we must discuss systems in which interference is unavoidable. Suppose that you create a massive amount of interference solely to disrupt communications. The military world calls this electronic warfare; the process is called jamming. Over 50 years ago, this problem forced military communications specialists to rethink the orthogonal architecture of wireless communications. One result was a closer examination of interference itself, and the other was a non-orthogonal process called signal spreading.

Self-interference, or fast fading, is the biggest problem the wireless engineer faces. The problem can be attributed to multipath propagation of the signal since other interference can be controlled or buffered from the transmitted signal. Using the space, time, and frequency dimensions, fade can be defined in terms of coherence values. These values specify a boundary that describes the signal's typical fade characteristics. If the signal size is close to the fade size, fade will significantly affect the signal size. However, if the signal were spread out and became much larger than the fade dimensions, a smaller percentage of the signal would be affected. This is the process used in spread spectrum systems of today.

Signal spreading was only part of Shannon's original work. He also discussed managing interference by averaging its effects and making it look more like noise. This process is very similar to the diversity solutions discussed earlier. Frequency hopping deals with frequency and space dimension interference while signal interleaving deals with the time dimension interference. In these cases, the result is to spread out the error and make it less pronounced.

Dealing with interference has led to considerable controversy over whether the interference structure should be determined and then cancelled out or simply mixed together with the signal like noise and then cleaned up using noise-oriented countermeasures. Calhoun cites several scholarly works on the subject of noise versus interference, and which one is worse. Shannon refers to white noise as "worst among all possible noise" while Viterbi calls it "the most benign of interference[s]." Regardless of which view you take, the current view is to mix everything together and use noise-oriented countermeasures to decipher the signals. Interference structure determination and cancellation might well be the solution in the next generation of wireless communications systems.

Three Flavors of Signal Spreading

Since there are three dimensions in which spreading can occur, there are different signal spreading systems.

- Direct sequence spread spectrum (CDMA, wideband CDMA, and cdma2000) forces a multiplication of the signal in the time domain that spreads the signal in the frequency domain.
- Orthogonal frequency division multiplexing (discrete multi-tone used in digital subscriber lines) uses a forced multiplication in the frequency domain to spread the symbol in the time domain.
- Forced spatial spreading uses forced spreading in the space domain to increase capacity. This process is also called multiple inputs/multiple outputs (MI/MO), space-time coding, and transmitter diversity.

Regardless of the dimension being spread, all of these systems abandon the philosophy of orthogonality (i.e., no buffer, no guard bands, and no cell reuse distances).

Calhoun begins his discussion of signal spreading by discussing stereo systems and hearing. We will not repeat the discussion, but think of the fact that humans have two receivers (ears). Add to this multiple speakers, multipath propagation, and signal processing by the brain, and you can see how the analogy plays out.

In direct sequence spread spectrum we begin with a vocoder data stream of 10 kbps. If we were to repeat each bit from the vocoder 100 times, the resultant data rate would be 1000 kbps. In effect we have spread the frequency spectrum from around 10 kHz to 1 MHz. (See Figure 9.) The spread signal is now unaffected by small pockets of interference—sort of like navigating Vermont potholes with wide tires versus narrow tires.

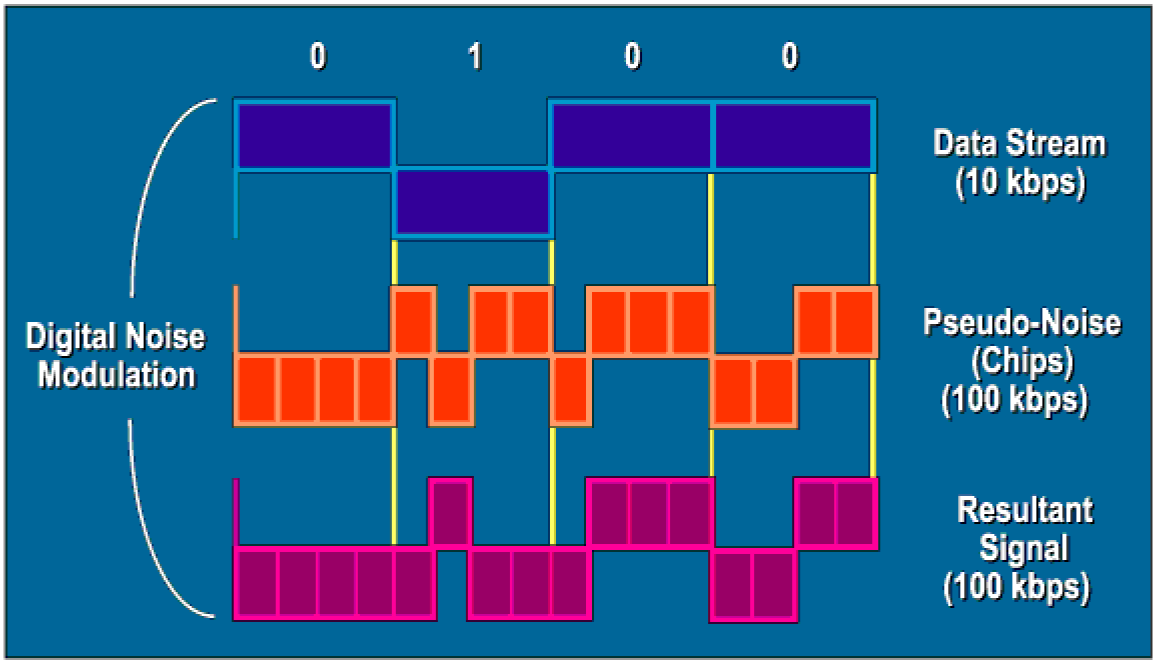

Figure 9: Direct Sequence Spread Spectrum

There are several positive effects due to signal spreading.

- Flat fading: The signal spread is wider than the interference (e.g., potholes are small in relation to the tire width).

- No distortion: Each pulse is so short relative to other time-based parameters of the system (e.g., motion of the handset) that the pulse arrives at the receiver before the channel characteristics can change.
- Favorable trade-off of bandwidth for power: The significant spreading allows for very low power operation, which cuts down interference and extends the handset battery life.
- Processing gain: This is the ratio of the spread bandwidth to the unspread bandwidth. The redundancy from the spreading creates a stronger signal.
- Potential for more information to be transmitted using more elegant coding schemes: Use the redundancy to increase the information carrying capacity.

All things considered, the simple notion of spreading the signal produces some remarkable results.

The second signal spreading system, orthogonal frequency division multiplexing (OFDM), works on the signal in the frequency domain to create a spread signal in the time domain. Calhoun suggests that we imagine direct sequence spread spectrum as a piano that has all 88 keys tied together. Thus with one motion all 88 signals are transmitted. Now suppose that each key is depressed independently and only one channel's worth of information is transmitted. Unlike traditional frequency division multiplexing where one channel is assigned to one user, OFDM assigns all channels to one user. This would imply that the user would need 88 transmitters and 88 receivers. One can imagine that all these transmitter/receiver pairs would result in an expensive system, especially if we talk about hundreds of channels.

The transmitter/receiver solution comes first from the work of Fourier who noted that all signals were a composite of sine waves of different frequencies. He observed that signals could be broken into their component waves (the Fourier transform) or created by combining the component waves (the inverse Fourier transform). Unfortunately the process is time consuming and were it not for the fast Fourier transform algorithm of Cooley and Tukey, this solution might never have been used.

In short, the inverse fast Fourier transform algorithm combines the channels into a single complex waveform. The composite signal is sent from one transmitter to one receiver. At the receiver, the fast Fourier transform breaks the composite signal into its component parts.

OFDM and other multicarrier techniques create opportunities to shape the signal to the shape of the channel—maximize the good parts and minimize the bad parts. Returning to the Vermont potholes, imagine that you are driving down the middle of a road that has potholes on the left side but none on the right side. The potholes would govern your speed. Now imagine that the road is split into two parts—one with potholes and one without. On the pothole-free side you drive fast and on the side with potholes, you drive slowly. But, the cumulative effect is a faster speed than you had in the first case. Once again, we spread the signal to minimize the effects of interference.

The third system, forced spatial spreading, is relatively new and has several names and flavors. Transmitter diversity, the simplest to understand, uses multiple transmitters to spread the signal in space but not in frequency. Each transmitter sends the same narrowband signal to the receiver. The multiple inputs/multiple outputs version increases the number of transmitters and the number of receivers operating in the same physical band. The more transmitters, the better, and capacity is increased without an increase in bandwidth.

Conclusion

Calhoun observes that it would be nice for the play to end with signal spreading riding off into the proverbial sunset. However, this scenario might not be the end of the story. Verdú proposes multiuser detection as a way to determine the interference structure and then cancel it. Abramson proposes a spread ALOHA multiple access system that has one spreading code for all users. Viterbi proposes that each CDMA user be given a unique time slot so that the fixed transmitter power can be reduced. Chuang and Sollenberger propose that OFDM use dynamic channel allocation to avoid interference. Each of these systems relies on some form of orthogonality to deal with issues of interference.

After all of these discussions, we need to ask: “Where is Shannon?” For the answer, I turn the word processor over to George Calhoun for some closing comments.

Calhoun’s Comments

There is no question in my mind that the most interesting developments today in communications theory are being driven by the challenges of "engineering" the un-engineerable wireless channel. This is bringing Shannon's ideas—enunciated more than fifty years ago—into much closer contact with reality, which inevitably will enrich and extend the theory in many interesting ways. Hence the phrase "Post-Shannon" is not intended to suggest that classical information theory is somehow obsolete or incorrect. On the contrary, all theoretical work in this field today must begin with a foundation in Shannon theory. But it is also true that some of the important assumptions that Shannon saw fit to make in 1948 in order to simplify his analysis might no longer be appropriate to the engineering challenges facing the industry today. A simple example (discussed at length in the book) is the assumption that source coding and channel coding are independent processes that should be executed in separate signal processing stages. Since the introduction of trellis coding in the 1980s (which broke the previously projected capacity ceilings of certain types of channels), this assumption has been increasingly questioned, and the creative use of joint source/channel coding has become a standard signal processing strategy in a wide range of applications.

Over the next few years, therefore, I predict that we will see a growing recognition that by modifying some of the foundational assumptions, we will be able to expand the scope of the theory to address old topics in new ways and generate new results that will sometimes appear to break the boundaries of classical Shannon capacity limits and other theoretical parameters.

Feel free to contact me at geo@georgecalhoun.com with any comments.

Final Comments

I would like to thank George for taking the time to read this paper and provide some closing comments. If you read his latest text, be sure to read the footnotes as they offer numerous insights into wireless communications and are just fun to read in some instances.

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About Paul Whalen

Paul Whalen has over 25 years' experience in telecommunications as an instructor and consultant. Over the past several years, he has used his expertise in wireless communications and business strategy to create and deliver courses that focus on the issues facing companies involved in the wireless communications marketplace. Business leaders rely on Paul's insights as they determine their business and technology strategies. His knowledge of convergence, both voice and data and wireline and wireless, has allowed him to create a variety of business strategies. As CEO of Hill Associates, he also brings a strong sense of business reality to the classroom. His in-depth knowledge of the telecommunications regulatory scene allows him to put a strategy into the correct regulatory perspective. Paul is also well versed in broadband communications and the IBM networking technologies.

A dynamic and energetic presenter with a broad perspective on technology and business, Paul is capable of dealing with technology issues and learning issues in the classroom. He has developed educational programs for technical and non-technical audiences that range from five days to over sixty days. He has been with Hill Associates since 1984. Before stepping into the role of CEO, Paul served as MTS, Senior MTS, CFO, the Director of Sales and Marketing, and the Director of Planning.

Prior to joining Hill Associates, he was the founder and CEO of Interactive Computing of Vermont and the Associate Director of Academic Computing as well as a lecturer in Computer Science at the University of Vermont. He holds a B.Sc. from Carnegie Mellon University, M.Sc. and Ph.D. in Mechanical Engineering from the University of Vermont.

Paul is a registered Professional Engineer in Vermont. He is a member of the American Society of Mechanical Engineers, the National Society of Professional Engineers, and the Vermont Society of Professional Engineers. His hobbies include hiking, canoeing, camping, antique collection and restoration, reading, and traveling.

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