Cell phones 101:

EpiphanyBySteveLee.com

Introduction:

Unlike most of the other projects described in this section of our website (EpiphanyBySteveLee.com, misc), this document offers something of a basic tutorial, with the topic being the now ubiquitous cell phone. With virtually everyone today carrying a cell phone (in some cases more than one), many of us have become almost addicted to using these little gadgets. And yet if you asked the average person on the street how something barely larger than a candy bar or pack of gum can allow you to instantaneously talk to someone on the *other side of the planet* at the simple push of a button, 99% of those people wouldn't have the foggiest idea. We hope the following "*information*" (loosely termed) helps remedy that situation.

The first known use of "radio waves" (a.k.a. "ElectroMagnetic waves") to convey information across any significant distance was back in the 1890's when Guglielmo Marconi and Nikola Tesla independently began experimenting with high power alternating electrical currents, and found that if they got the currents to alternate at a high enough frequency (e.g. a million cycles per second) on a long wire or metal structure (the antenna) roughly a quarter wavelength[1] tall, an electronic circuit some distance away tuned to that same frequency would resonate with the energy radiating off the antenna[2]. Perhaps taking their hint from the Reeses Peanut Butter Cup people (or, maybe not), someone then combined the decades-old technology of wired telegraphs, with this rather odd "spark-gap" phenomenon, and the first new-fangled wireless telegraph was born.

(As an aside related to the wireless telegraph, we note that contrary to Hollywood's version of things, rumor has it obsessive texting on his wireless telegraph by the captain of the Titanic is what actually led to their hitting that gigantic *mountain* of ice, and *not* Kate Winslow's clutsy bow surfing routine. Seriously, in her corset she is all of what, *three* inches wide at the waist...)

Not long after that, someone had to "one up" Marconi and Tesla, and decided to combine Alexander Graham Bell's toy with the high frequency AC generator, creating the first wireless voice transmitter. This then led to broadcast AM radio, the situation comedy, television, *Danny Partridge*, Swanson TV dinners, Thurston Howel the Third, and the general breakdown of society as a whole (though not *necessarily* in that order).

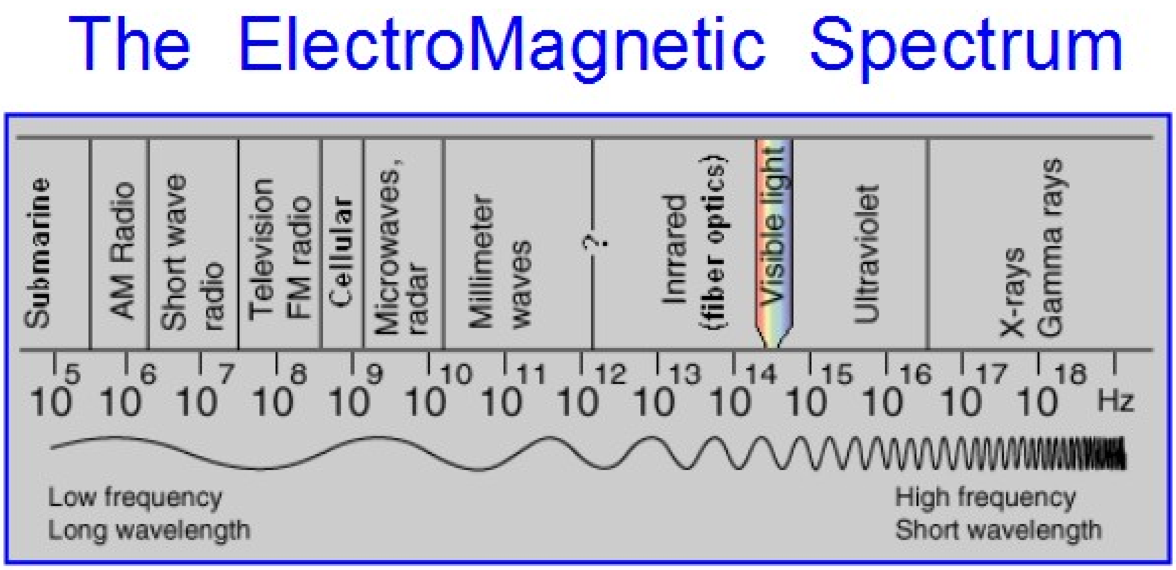
Anyway, somewhere along the line (i.e. circa WWII), someone got the *brilliant* idea to put one of those wireless transmitters and a receiver into a shoebox-sized *monstrosity,* who then gave it to some GI. This GI, while stuck in his fox hole bored out of his skull, then used

1 One wavelength is the distance between two peaks of the wave as it travels. Therefore, Wavelength = Speed/Frequency = C / F = 300 million meters per second /1 MHz.

2 Tesla actually went so far as to build a few gigantic towers topped with oblate metal spheres which he powered in an attempt to create a network of such towers to *electrify the atmosphere*. His goal in doing so was to prove that people miles away could pull this energy out of the atmosphere to power light bulbs and other electrical equipment. Fortunately for us, this technique never quite caught on as a power distribution system (too much loss between transmitter and receiver to deliver the kind of current needed), but it did prove it was possible to use this technique to instantaneously transmit information across great distances.

the device to call one of his buddies back at “artillery support” to reminisce about Papa Ginessio's peperoni pizza (with extra anchovies) – and okay, maybe call in a Howitzer round or two. Years later, while hunched over his desk at RCA (or Motorola, or Bell Labs... the details get a bit fuzzy), still longing to wrap his gums around one of those mouth-watering Papa Ginessio's pizzas (with extra anchovies), this same guy recalls that sleek shoebox-sized *monstrosity*. Envisioning it as a “portable” wireless phone, he decides to drop a suggestion in the suggestion box. And the rest is, as they say, “history”.

Well, at least that's how I remember it. (Okay, so maybe there were anchovies involved, and maybe not, but either way, you get the general idea. Seriously, who quibbles over a “few” *minor* details like anchovies, and TV dinners, and texting over a wireless telegraph while watching the hypnotic swirl of a flying corset? *Who's telling this story*?)



<u>The humble little “ElectroMagnetic wave”</u>:

So, what exactly are these “radio” / “ElectroMagnetic” waves, and how do they enable us to send voice signals (or pages of text, or pictures, etc.) around the globe? Perhaps the easiest way to answer that question is to follow “Doc. Brown's” (Christopher Lloyd's) lead in “Back to the Future”, and demonstrate the concept with a little “*science experiment*” (ah, *without* the Delorean this time).

Step 1, grab one of the *many* latex party balloons you have leftover from your last birthday *fandango*, blow it up and tie it off.

Step 2, now rub the balloon *vigorously* through your huge quaff of downy-soft fluff of pony hair.

Step 3, bring this now electrically charged balloon *close to* (but without touching) one of those gigantic mounds of leftover paper birthday party confetti dots piled up all around your room, and observe what the paper confetti does as the balloon approaches: If you performed the highly complex task outlined in step 2 *correctly*, you should see the paper dots begin to stand up and lean towards the charged balloon (the same effect can be demonstrated by bringing the charged balloon next to a friend's hair, should the dog and/or kids have eaten all of your stash of party confetti, *yet again*).

Explanation: The rubbing action of the balloon through your flowing mane of pony hair (or mangy wad of cat fur, whichever the actual case may be) effectively accumulates electrons on the balloon at the point of friction. Since the balloon is latex (a non-conducting material), these electrons can't flow away from the point of contact, leaving them all munched up in each other's face in a large pile accumulated at that spot on the balloon. When you bring that group of charges close to the paper dots, the charges in the molecules in the paper dots "feel" the presence of the charges on the balloon, and are drawn to them (somewhat like the attraction between opposite ends of two magnets). If you are particularly talented and you apply yourself with great passion, you might even be able to get the dots to stand up and do a little rhythmic dance (though please, anything but the *Macarena*).

(As another aside, we note that this charge accumulation phenomenon is the same effect responsible for lightning, only involving much, *much* larger numbers of charges displaced by the friction involved in flowing columns of dry air. We have it on good authority from our buddies at Area 51 that it might also, *possibly,* have something to do with trans-dimensional portholes and the whole *Philadelphia Experiment* thing going *sideways*... though we're not really suppose to talk about that.)

The fact that the accumulated charges on the balloon can influence other charges around them *without* making any direct physical contact, leads us to conclude that there must be some kind of "electric field" radiating out from the charges on the balloon that exerts a force on all other charges in their immediate environment. As you might have guessed, the strength of this field is directly proportional to the number of charges accumulated (**q**), and inversely proportional to the distance squared (i.e. $1/r^2$) between the charges and the confetti dots (with a few proportionality constants thrown in to make all the numbers work out):

$$E_{(r)} = \frac{q}{4\pi\epsilon r^2}$$

By moving those charges back and forth quick enough (say at a few million times a second) and in specific patterns, we can effectively create one of those useful little *undulating* radio waves. A "few" more "*minor*" *tweaks* to your wireless balloon telegraph, and you're "practically" on your way to creating your own smart phone.

Being as sharp as you are, you have *no doubt* realized by now a *slight* little kink exists in our attempts to use this approach to create an effective wireless network, namely the fact that *any* radio wave we thus create inevitably becomes weaker with distance squared ($1/r^2$). Though our cell phones are *slightly* more sophisticated than a charged bouncing balloon, it's pretty obvious the tiny batteries in these phones are not capable of sending a strong enough radio wave more than a few miles for any sustained period of time to enable us to carry on any meaningful long-term conversation.

The solution to this $1/r^2$ distance problem[3], is to either equip our wireless phones with a suitcase-sized battery to enable them to transmit more powerful fields over larger distances, or position a lot of radio receivers throughout any area where we might want to be able to use our cell phones. Holding a Samsonite steamer trunk next to your head while reading the newspaper [while driving your car] being as socially awkward as it is, people opted for the latter option. Hence the use of local cellular base station transmitters/receivers (and their associated antenna towers needed to see over all the clutter scattered around them). And of course this cellular network equipment also includes the huge array of fiber optic cables and switching offices connecting all those base stations to the pre-existing phone company and

3 Actually, the path loss is worse than $1/r^2$ when you include all the "junk" in the environment that scatters and absorbs radio waves, being more like $1/r^4$ in most suburban environments, and possible $1/r^6$ in urban areas.

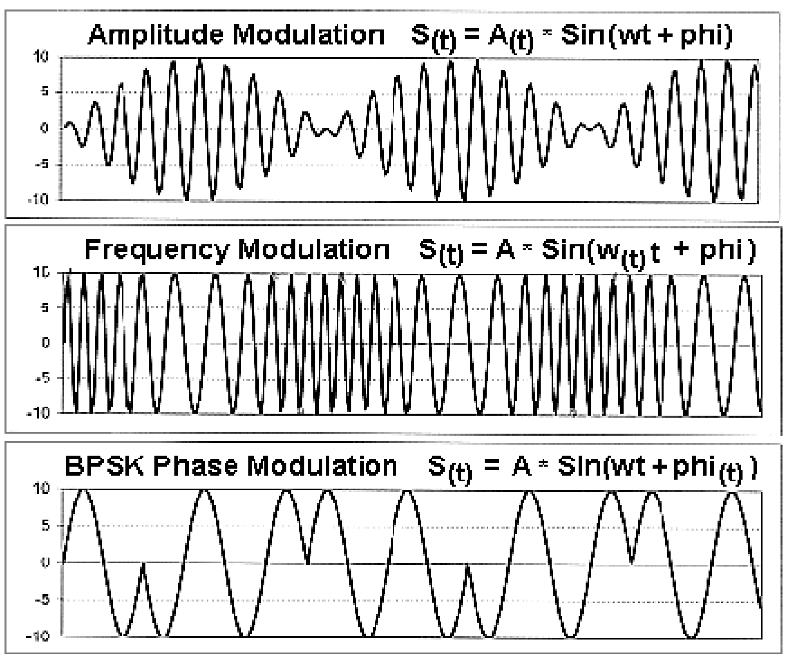
internet infrastructure.

Sending messages:

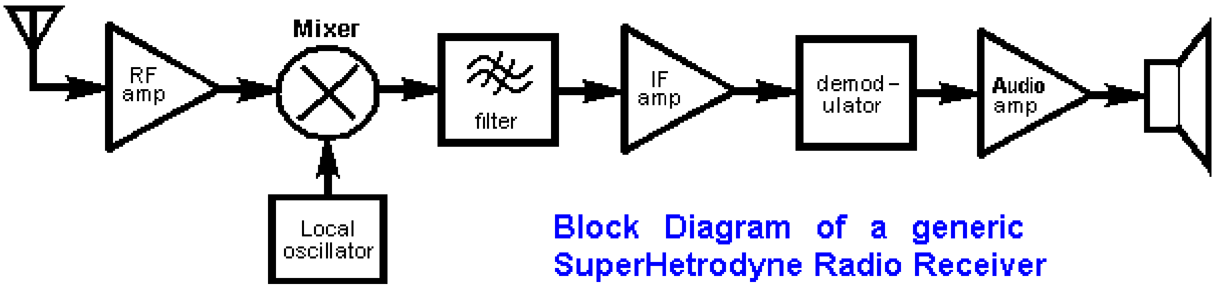
Now that we have developed a network of base stations across the globe and the army of balloon/shoebox cell phones needed to establish a wireless link between various users, how exactly do we use the radio waves to carry our voice (or text message, internet traffic, videos, etc.)? Truth is, there are many different techniques currently in use that enable us to do that. In general though, they all effectively use the radio/electromagnetic wave as nothing more than a *transporting* mechanism to *carry* our information from point “A” to point “B” (hence the term “carrier” is often used to describe the radio waves we generate). This is analogous to using a blank sheet of paper as a way to carry a message from one person to another. As a blank page, this sheet of paper itself contains no information. It is only after we “modulate” the “blankness” of that paper with ink or graphite (or for some of you, perhaps *crayon*), that the paper becomes the vehicle we use to carry our intangible thoughts and feelings across some distance to the object of our desires (or the trash collector, whichever the case may be).

With the whole “modulating the carrier” concept in mind, the first thing we do to enable our radio transmitter to send information on its way, is to generate a continuous radio wave which we will then use as our *carrier*. This carrier is typically nothing more than a steady sine wave tone oscillating at say 100 million “Hertz” (or “cycles per second”, which would place it right in the middle of the FM broadcast band). We then take this continuous oscillating tone and “modulate” it in some fashion to embed our information on the “blankness” of that carrier.

As there are many different ways of embedding information on a blank sheet of paper to “modulate” that “blankness”, there are also many different ways of modulating the steady tone of a radio wave carrier in order to use it to convey information. This includes changing the carrier's amplitude (i.e. “Amplitude Modulation” or “AM”), or its frequency (i.e. changing its “cycles per second”, giving us “Frequency Modulation” or “FM”), or perhaps its phase (i.e. “Phase Modulation” or “PM”).



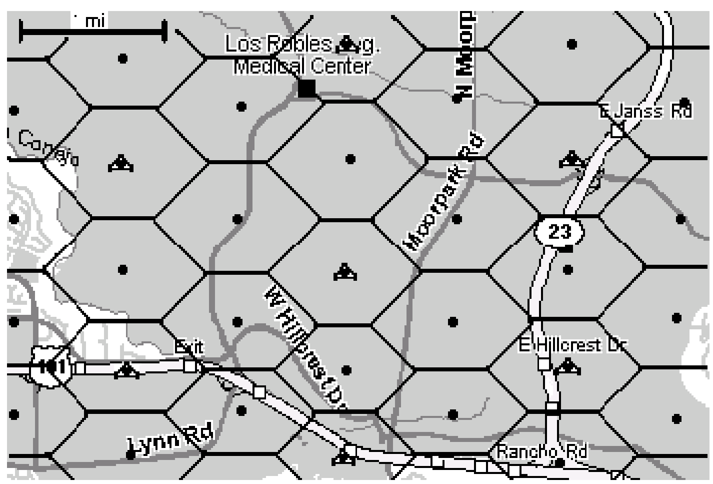
Of course the corresponding receivers we use at the other end of our radio link must be designed to be able to interpret whatever type of “modulation” we are using, stripping the information off the carrier, and presenting it to us either as the sound of the voice or music being sent by the transmitter, or as digital bit streams that are then processed by “higher” layers in our receiver.



Block Diagram of a generic SuperHetrodyne Radio Receiver

And that essentially brings us up to the 1980's.

Right around 1980 however, “somebody” at Bell Labs (possibly inspired by the highly memorable and *alluring* C.W. McCall top-40 smash hit “*Convoy*”... or, possibly not), decided we needed something a little more sophisticated than a shoebox-sized walkie-talkie or CB radio to wirelessly connect many people across large distances[4]. Enter the concept of the “1G” “Cellular” wireless phone network.



© 2002 "Spread Spectrum CDMA", Steve Lee (McGraw-Hill inc.)

The key aspect of the “Cellular” network design, was that it reduced the power of the mobile phones down to only a few Watts (as opposed to 50-100 Watts in older car two-ways). This had several specific consequences, namely it made them less expensive, a bit more portable, and (most importantly) capable of accessing the limited number of available channels over only *short distances*. To deal with the shorter access distance, this cellular network design required an operator to build multiple base stations across the serving area, typically only a few miles apart. To eliminate the need for a live operator to connect the wireless link to the phone lines, the cell phones and network call processors borrowed a few concepts from older mobile systems, including the use of a microprocessor to enable automatic channel assignments, etc.

Building out a cellular network complete with all the required base stations every few miles was a very expensive proposition, limiting the location and size of most initial networks to areas with the greatest population density (i.e. more “bang for the buck” for the network builder). However the significant reduction in cost to the user that came with the smaller and

4 To be accurate we note that older mobile telephone systems did exist in the 1960's and 1970's, however they required 100-Watt boat-anchor transmitters to operate, and when transmitting tended to suck the car battery dry in minutes. Worse yet is the fact that when in use, only a handful of users could use the limited number of channels available throughout a 30- to 50- mile radius.

thus cheaper handsets, made the use of portable wireless phones around dense population centers almost affordable. At the same time, this growing user base translated to a growing revenue base, helping to fund the expansion of these new networks well past the metro boundaries into the adjacent suburbs. As more and more people began using cell phones, the economy of scale that comes with *tripling* and *quadrupling* the number of paying customers on a given network (coupled with free-market competition), drove the cost of cell phones down even further, while also allowing the networks to expand out across most of the country. By the mid 1990's however, the number of cellular users had exploded, creating a whole different type of technical challenge for the network operator.

Unlike a wired phone system, wireless networks had only a *finite* number of radio channels available to parse out to all the users now crowding the airwaves. During peak hours (e.g. between 4pm and 6pm local times) in most cities, the demand by all the users wanting to make a call soon began to deplete all the available channels, leaving many frustrated users being denied access (i.e. experiencing the dreaded “blocked” call). Enter “2G”.

<u>2G / 3G cellular systems</u>:

By the mid 1990's, this saturation of available cellular channels motivated a strong push to implement “Second Generation” (2G) technologies in order to develop a way to pack more users into the limited number of radio channels. As a result, two dominant 2G schemes emerged: TDMA/GSM[5] (Time Division Multiple Access/Global System Mobile) and CDMA (Code Division Multiple Access). Both of these signaling schemes enabled more users per channel by developing more efficient ways of utilizing the available radio spectrum.

The most obvious opportunity was found by considering the normal flow of our speech. During a typical conversation, most *normal* people talk one at a time (i.e. one person talks for a moment while the other listens). This means that roughly half the time, any given active 1G cellular radio channel was carrying no useful information at all, and as such was being wasted. In an attempt to make use of this wasted channel space, the above mentioned 2G schemes used several techniques designed to recover some of this wasted resource through improved efficiencies in the wireless connection.

One technique used by both of the above mentioned schemes, was to employ what is known as a “VoCoder”. A VoCoder (or “Voice Coder”) effectively takes the user's digitized vocal sounds (e.g. “Kah”, “uuh”, “LL”, “ ”, “Duu”, “Dah”, etc.) and relates each sound the user makes to those in a table of vocal sounds containing all sounds used in human speech. Having identified and related each vocal sound used in a sentence to the corresponding sound in this speech table, the cell phone then sends the table *index* representing each vocal sound, instead of sending the actual sounds themselves (allowing the phone to significantly compress the signal being sent). At the receiving end, the opposite process is performed, effectively reconstructing the sounds sent by the sender into a synthesized version of the original sentence.

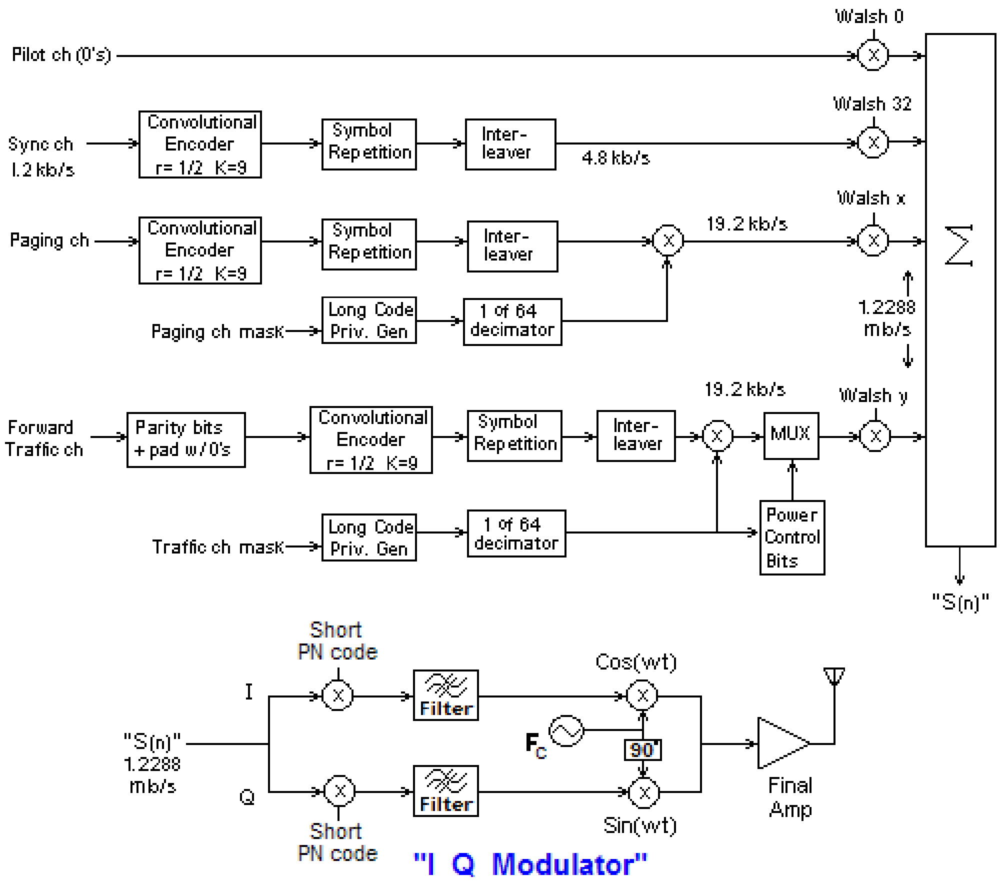
In addition to compressing the voice signal down via the VoCoder, additional channel efficiencies were developed by modifying the methods used to modulate the transmitted carrier. Though both 2G schemes focused on enhancing the modulation efficiencies, each approached this aspect of the process very differently.

<u>TDMA/GSM</u>: Under the TDMA/GSM approach, the radio channel is sliced up into short “Time Slots”, and each user's phone then compressed and sent all their digitized VoCoder

5 GSM being the European implementation of TDMA.

data during one of these Time Slots (as assigned by the network base station). Using this approach, operators were able to increase their calling capacity by roughly three times the capacity they had under the first generation analog cellular systems. This was later enhanced further to achieve roughly a five-fold increase over 1G.

CDMA[6]: Under the CDMA approach, all active users are on the *same* radio channel at the *same* instant in time. To enable the receiver to separate out one user from the other (as well as recover some of the transmitted energy previously lost by scattering off objects in the environment), CDMA introduced a unique partitioning technique on top of the radio channelization that involves assigning each active user their own "orthogonal" digital code. These orthogonal codes are known as "Walsh Codes".



Spread Spectrum CDMA TX block diagram

For those not familiar with the concept, orthogonality is a mathematical property certain mathematical functions share between them. For example, Sine(x) and Cosine(x) are orthogonal to one another, as are Sine(x), Sine(2x), Sine(7x), etc.[7] If the sum of the products of any of these two functions over a full period of their cycle is zero, then they are orthogonal. For example:

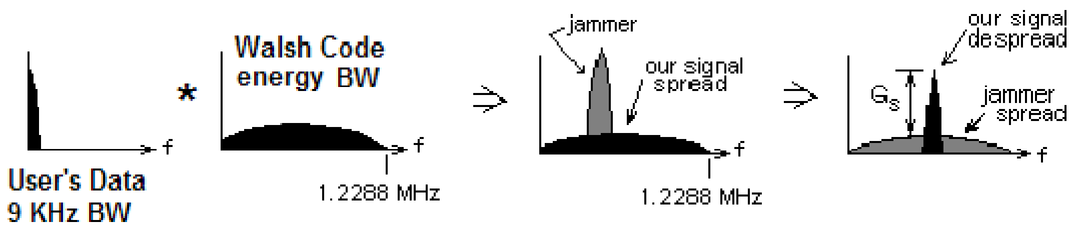
6 For a more detailed description of CDMA, see this author's prior work "Spread Spectrum CDMA", McGraw-Hill 2002.

7 Other common examples of orthogonal functions now heavily exploited in physics and engineering include Bessel Functions, Spherical Harmonics, Legandre Polynomials, Chebychev Polynomials, etc.

$$\sum_{K=0}^{K=2\pi} \text{Sin}(akX) * \text{Sin}(bkX) = 0 \quad \left[\begin{array}{l}\text{if "a" and "b"}\\ \text{are integers}\end{array}\right]$$

In this notation, “k” is nothing more than an integer which we use as an index for each of the Sine() terms, and “∑k“ tells us to sum up all the Sine() products (e.g. Sine(a2X) * Sine(b2X) + Sine(a3X) * Sine(b3X) + Sine(a4X) * Sine(b4X) + Sine(a5X) * Sine(b5X) + … etc.).

At a CDMA base station, a user's digital stream (running for example at 9 Kb/s) is combined with its assigned Walsh Code (running at 1.2288 Mb/s). The resulting product produced from this combination effectively inherits the characteristics of the two inputs. In other words, the product of this combination contains all of the complexity in the user's voice information (processed by the VoCoder), *plus* the orthogonality of the Walsh Code. Also, when the two are thus combined, the output ends up running at the rate of the Walsh Code (i.e. 1.2288 Mb/s), effectively spreading the energy of the user's digital stream (originally at 9 Kb/s in this example) out across a 1.2288 MHz bandwidth. This signal is then combined with a pilot signal, a synch signal, (etc.) and that net sum is then used to modulate a Sine(x) version of the main radio carrier and a Cosine(x) version of that carrier (in order to exploit the previously mentioned orthogonality between Sine(x) and Cosine(x) to boost our signal strength at the receiver). This split modulator is known as an “I Q Modulator”, and special care must be taken to insure both paths through the modulator experience exactly the same delay and amplification (or any imbalance will create noise that will affect other users). The two I and Q modulator outputs are then combined, amplified and sent up the antenna where it is all radiated out into space (see the TX block diagram above).



At its destination, the cell phone's receiver antenna pulls in the energy of this now weak signal and applies the same Walsh Code to it again. This *second* application of this specific Walsh Code at the receiver effectively *undoes* the first application of this Walsh Code applied at the transmitter (this reversal effect is another consequence of the orthogonality), de-spreading the user's original 9 Kb/s digital stream back to its original 9 Kb/s bandwidth. Any other radio energy pulled down by the receiver's antenna (including the other user's energy on that same channel, or “jammer” signal, etc.) go through this same Walsh Code application. The difference for these unwanted signals however is that this is the *first* time this Walsh Code is applied to them. When they are combined with this Walsh Code for their first time, their energy is spread out (as happened with the original signal back at the transmitter).

Now that the unwanted signals is spread out and the desired signal is de-spread, the desired signal ends up being over 100 times stronger than the unwanted energy. This “Spreading Gain” makes it very easy for the receiver to isolate and select the specific user's signal as needed and reject all others. And with the Spreading Gain giving the desired signal such a tremendous advantage over the unwanted signals at the receiver, we can now afford to add additional users on the channel without degrading the connection for the desired signals, giving us our much needed boost in channel capacity.

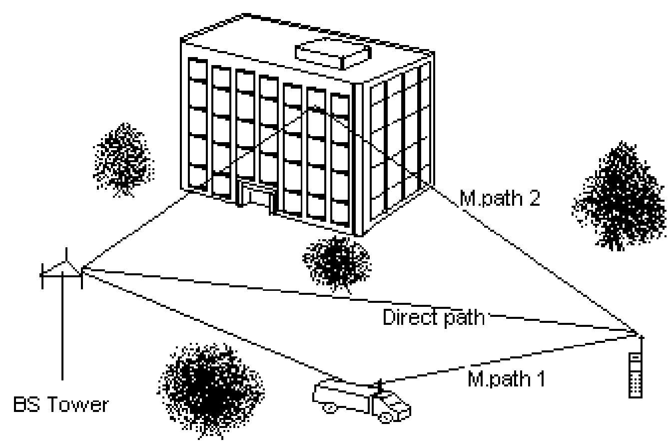
In addition to providing Spreading Gain while reducing the channel noise, having all the users on the same radio channel using orthogonal Walsh Codes, allows CDMA to do one other useful thing: execute what is known as a “Soft Handoff”:

Soft Handoff:

When a mobile phone moves near the edge of a cell's coverage, that phone typically struggles to hear the base station even as it reaches its maximum power output trying to send a strong enough signal back to the cell to be heard. Worst yet is the fact that in addition to struggling to overcome the greater path loss suffered while at the edge of the cell, moving cell phones typically travel behind buildings, or dense foliage, or hills, or down into valleys, degrading this wireless connection even more.

Having all the users sharing the same radio channel in CDMA allows the network to connect the mobile to several base stations nearest the phone and combine their signals to form a “Soft Handoff” between cells, and thus improve the strength of the connection for users in these weaker fringe areas. This reduces the number of drop calls, even as it helps reduce noise on the channel (by allowing the phone to operate at less than max power during the Soft Handoff).

Multi-path:



One of the biggest degrading effects affecting all *analog* wireless systems is the reception of energy that arrives at the receiver via multiple indirect paths (e.g. reflected energy coming off some distant building, passing trucks on the highway, etc.). Since energy that travels to the receiver via a reflected path travels a longer distance compared to the direct path, it arrives at the receiver *delayed* relative to signals that arrive via a direct line-of-sight path. When the direct path signal is combined with any other “mulit-path” signals in an analog wireless system (e.g. in the 1G cellular networks), the delayed signal typically degrades the direct path signal.

One additional advantage developed by applying the Walsh Code to our user's signal in the CDMA system, is that the Walsh Code effectively “time-tags” each bit of the user's signal before it is transmitted. As a result, if part of our user's signal comes to the receiver's antenna off an indirect “multi-path” route, we can exploit the Walsh Code time-tag to allows us to electrically isolate each signal path, and then re-sync and combine them at the receiver (using what is known as a “rake receiver”). In the process we recover more of the energy transmitted than we could do in an analog system (i.e. the energy from the direct path + the energy from the other “multi-paths”), boosting our desired signal all the more.

As a result of these signal strength gains, the CDMA modulated signal allows us to use less power to transmit information over the radio channel. Since the receiver is only interested in recovering the energy for the desired user's signal, all of the other user's signals on the same channel represent nothing more to it than noise. With these enhanced techniques however, we are able to transmit each user's signal with less power, reducing the overall level of noise the receiver hears on the channel as it hunts for its desired user's signal. Consequently, this lower noise level allows us to add even more users on each channel, effectively increasing each channel's capacity, as well as the overall cellular network capacity as a whole.

These improvements gave 2G CDMA roughly a five-fold increase in channel capacity over 1G (analog) cellular systems, while subsequent 3G implementations of CDMA (which added additional enhancements/efficiencies), provided roughly a ten-fold increase in capacity over 1G systems!

OFDM and 4G LTE:

Considering the information presented thus far, we see that each generation of wireless technology develops its improvements over the prior generations at a cost of increasing the complexity of the overall transmission process. However with the advent of Large Scale Integration (LSI) integrated circuit technology, virtually all of this increased complexity is handled inside a few LSI chips, making the development and operation of the radio side of a cell phone completely transparent to the network operator and the end users themselves.

With the advent of "4G" (Fourth Generation) LTE systems, it should come as no surprise that the wireless implementation of this scheme is dramatically more complex than any of its predecessors. We note in this latest transition however, that there was a significantly different driving force behind the change to this next generation wireless technology. Up to this point, all of the motivation for transitioning from 1G to 2G and then 2G to 3G cellular systems was to accommodate an increasing demand for voice calls. The drive behind moving to 4G however was not to increase voice capacity, but instead to address the new phenomenon of exploding data usage[8] which occurred not only due to the advent of the "smart phone" (and the many phone "aps" that came with it), but from wireless laptops, wireless tablets, and "machine-to-machine" (M2M) usage (e.g. autonomous vending machine stocking reports, automated toll booths, remote security systems, warehouse inventory tracking systems, etc.).

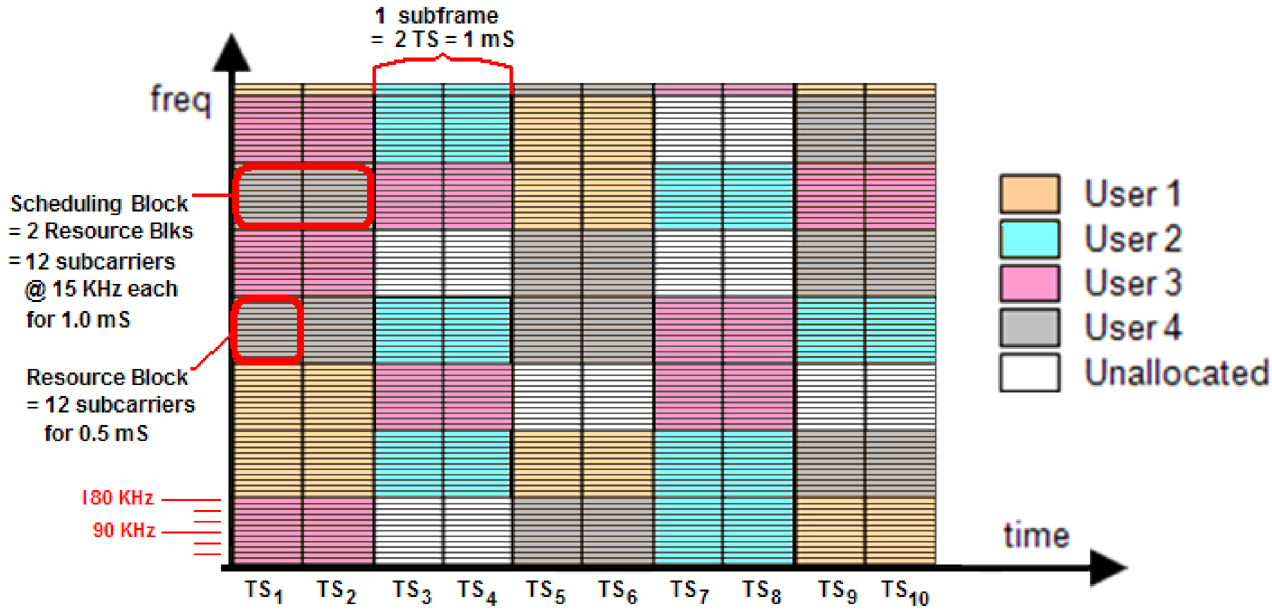
To accommodate this new explosion in data demand, 4G LTE adopted a dramatically different approach to the whole "modulate the carrier" thing. In essence, LTE broke the channel allocation process up into not only time-sliced segments, but now also "frequency-sliced" segments as well, dolling out portions of those frequency slices to each user during specific time slots as needed in groups known as "Resource Blocks".

Using a technique developed by the DOD in the 1940s known as Orthogonal Frequency Division Multiplexing (OFDM), the standards group that developed the LTE cellular protocol (the 3Gpp, or "3G Partnership Project") accomplished this "frequency slicing" by setting up an array of "sub-carriers" on each assigned radio channel. Exploiting the previously noted orthogonality between Sine(ax) and Sine(bx), all of these sub-carriers are specifically set up to be orthogonal to each other, allowing them to be spaced only 15 KHz

8 We note again for accuracy that previous generation cellular protocols had the capability of sending and receiving data, however the demand for that capability back them was relatively light. Those who designed the data capability into the subsequent generations did so more in anticipation of the yet-undefined need (almost following the notion that "if you build it, they will come"), many then found themselves waiting slack-jawed for the "killer ap" that would trigger the expected demand for data. Though not exactly what most had in mind, that demand boom eventually did come when the improved user interface offered by the "smart phone" hit the market. Unfortunately this became something of a "careful what you wish for" story, as many network operators found their networks soon being *crushed* by an exponentially exploding demand for data, particularly during peak hours.

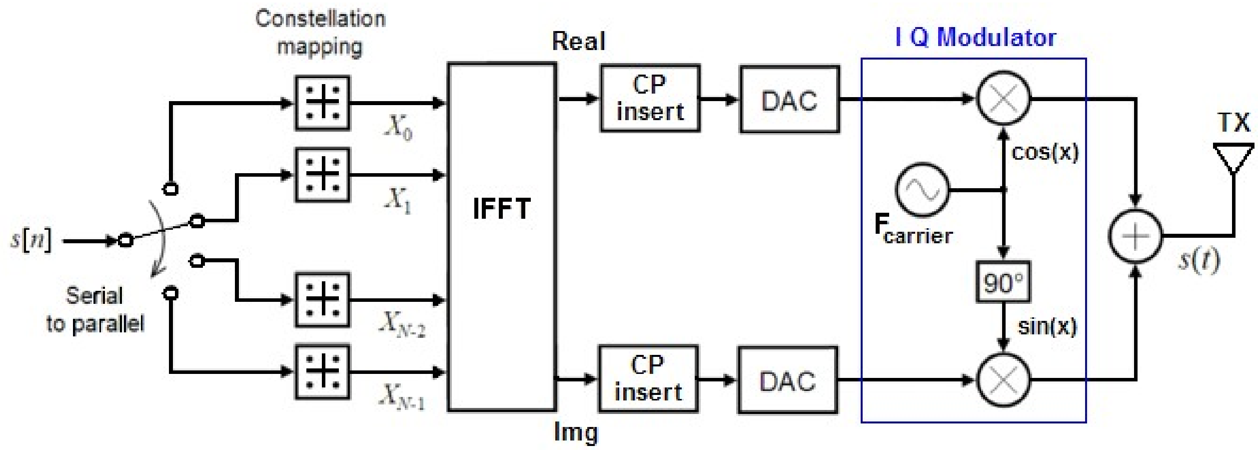
apart across the channel and still present minimal interference to each other.

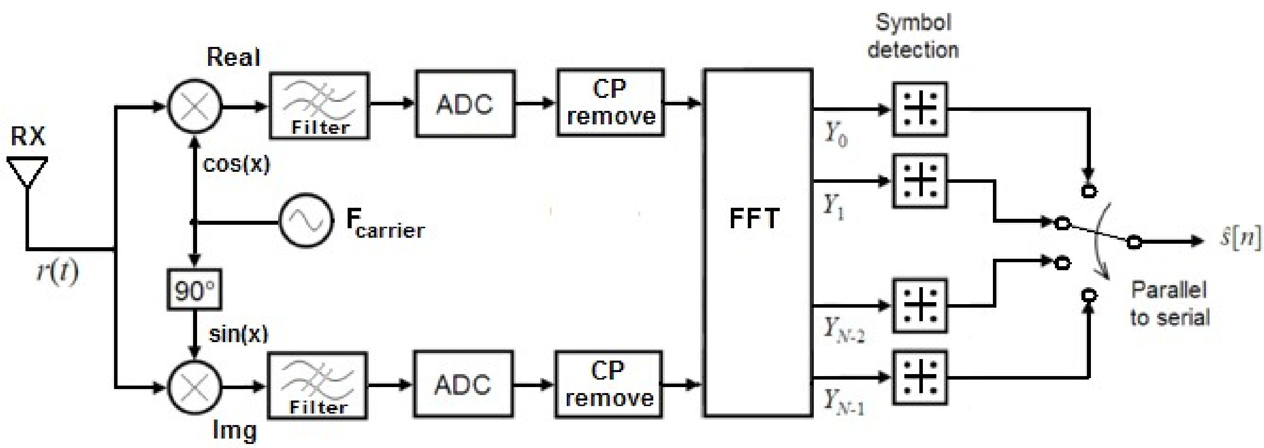
LTE groups 12 of these 15 KHz sub-carriers together over a single Time Slot (0.5 milli-Seconds), forming a single "Resource Block". As a result, a 10 MHz wide radio channel (for example) contains 50 Resource Blocks ([10 MHz – 1MHz guard band] / [12 * 15KHz] = 50 RB). Users are assigned Resources Blocks in consecutive pairs (i.e. in "Scheduling Blocks"), giving them as many RB's during as many Time Slots as needed (and *available*) to deliver all the data being routed to that user in as short a time as possible (i.e. with as high a throughput rate as possible).



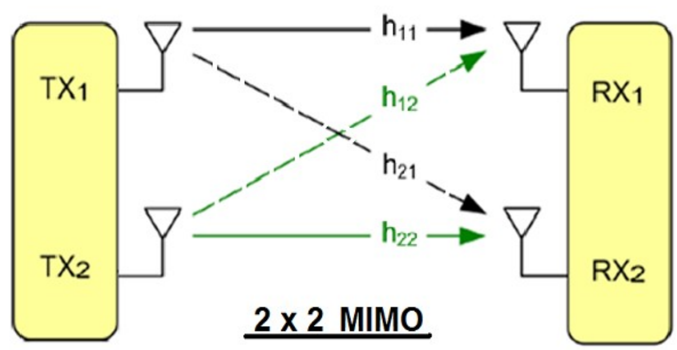
In a typical LTE transmitter, the user data stream is broken up into groups of bits (shown as the "serial to parallel" step in the diagram below), and then each of these groups of bits are applied to a specific 15 KHz sub-carrier in the Resource Block/time slot. The application of each group of bits generates a single "symbol" on each sub-carriers (i.e. modulating its phase and amplitude for one or more cycles). All of these modulated sub-carriers are then pushed through an "Inverse Fast Fourier Transform" (see the FFT tutorial on "EpiphanyBySteveLee.com", misc tab) to convert them from a group of individual sub-carriers, into a single time stream. A "Cyclic Prefix" is then added to the time stream that effectively puts a little padding before each "symbol" to deal with multi-path interference issues. The resulting digital stream is then converted into an analog signal in a DAC (Digital to Analog Converter) before it is then applied to the "I Q Modulator".

At the I Q Modulator, the main carrier is split into two related versions of itself: a Cosine(x) version and a Sine(x) version, allowing us to exploit the orthogonality between Sine and Cosine waves (as described in the previous CDMA discussion). These two modulated orthogonal versions of the main carrier are then combined, amplified and fed into the antennas to be radiated out into the environment. At the receiver, the reverse process occurs, as shown in the diagram below.





MIMO:

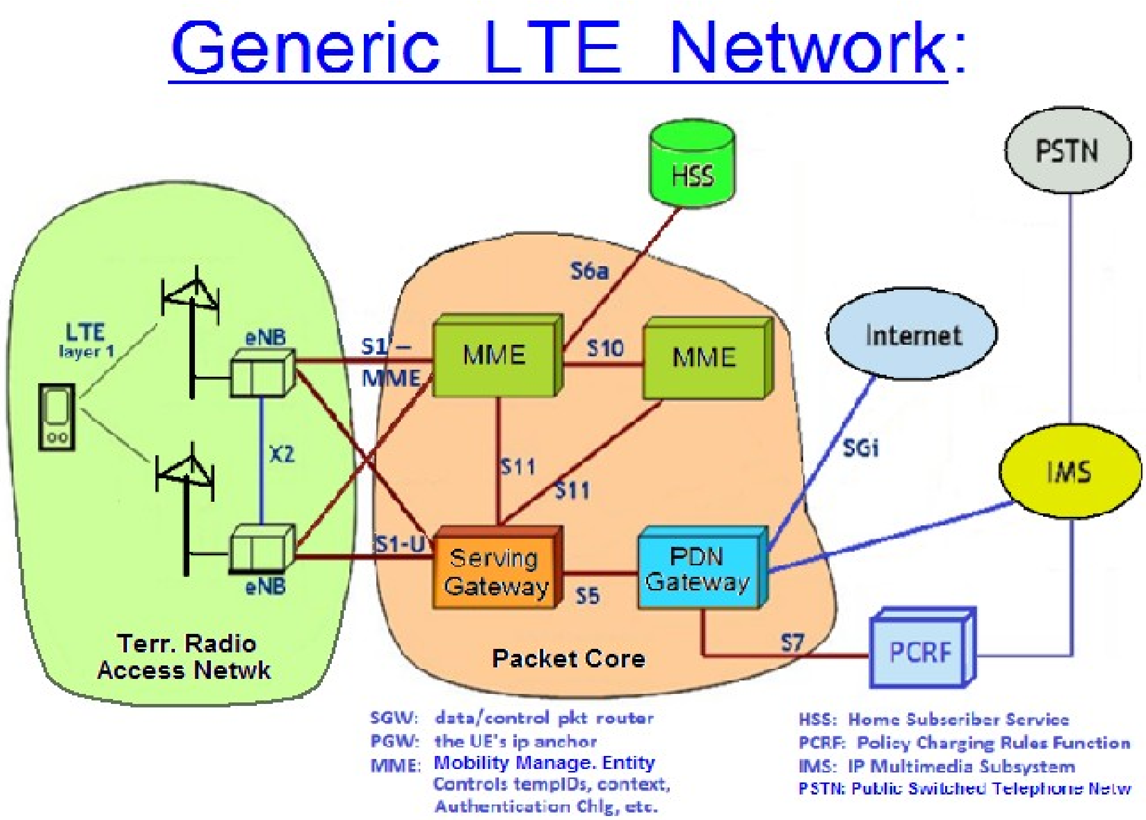


In addition to using orthogonal sub-carriers to enable a more flexible allocation of the channel capacity, the 4G LTE protocol also uses a technique known as "MIMO". MIMO ("Multiple Input, Multiple Output") incorporates multiple antennas on each sector of a given cell site in order to increase the overall throughput to each user. This increase in throughput is achieved by exploiting the receiver's ability to identify and isolate various multi-pathed signals coming into the receiver's antennas (using a technique similar to what was described in the previous discussion under the topic of CDMA, in which the Walsh Coded time-tagged signal enables us to use a "Rake Receiver" to isolate one multi-pathed signal from another).

In essence, MIMO allows the receiver to treat each multi-path signal as a separate and unique data "pipe", allowing the base station (a.k.a. The "eNodeB") to route multiple data streams to each user along each of these separate paths. In order to uniquely separate each signal stream, a separate antenna needs to be dedicated to each path. Two antennas at the base station/"eNodeB" and two at the cell phone (i.e. "2x2 MIMO") under ideal conditions thus provides two separate data paths, and thus enables *double* the throughput compared to a similar single antenna system.

Since the real world radio environment is constantly changing (e.g. mobile phones on the move, multiple objects moving around the user and thus changing the geometry of all the multi-path reflections, etc.), these reflected paths tend to only be stable for perhaps *tens* of milliseconds at a time. To deal with all the possible path changes that normally occur, the phone is constantly measuring and reporting the channel conditions back to the eNodeB. The eNodeB then uses all of this information to adjust power dedicated to this user, the MIMO transmission timing, etc., in an attempt to maintain the best signal at the receiver possible through all of the path reflection changes and signal fading.

Using 2x2 MIMO on a single 10 MHz wide channel, the current implementation of 4G LTE is capable of delivering a maximum total <u>sector</u> data rate of about 75 Mb/s under ideal conditions. Under a "normal" traffic load, that translates to a throughput to <u>each average user</u> of perhaps 5 Mb/s (typically). Under "perfect" signal path conditions and few active users, that rate can double or triple (ideally).



Unfortunately, as has been the case during each of the previous generations of cellular technology, 4G LTE wireless data is becoming something of a victim of its own success. As more and more users (and now more and more machines) begin downloading ever larger amounts of data, the load on each eNodeB has exploded. As more users demand more resources from a finite system, more congestion has developed, resulting in slower user throughput (due both to the finite number of Resource Blocks available shared amongst the larger number of *whiny* users, as well as the increased noise/interference each user experiences from the growing number of active users). This has motivated a number of enhancements to the current LTE protocol, leading to what is known as "LTE Advanced".

LTE Advanced:

In an effort to add even *more* capacity to the wireless link, as well as offer improvements that will provide even *higher* data rates, "LTE Advanced" includes a number of new features. These new features include:

> Carrier Aggregation – This feature will allow network operators to combine multiple radio channels at a given eNodeB (including channels that are widely separated across very different bands), effectively increasing the total available radio Bandwidth. Carrier Aggregation will give the eNodeB a wider pool of Resource Blocks to allocate as needed to the various users in its footprint, allowing it to more effectively assign users channels that offer only limited coverage (high band channels only travel short distances, which can now be assigned to users close to the cell site, while the lower band channels can be used for more distant users). The net effect is to provide flexibility in using the channels available to increase the total RF Bandwidth and thus provide greater capacity and throughput.

> Coordinated Multi-Point (CoMP) HO – This feature effectively attempts to enable something of a "Soft Handoff" similar to CDMA. The challenge however is that LTE deliberately places each user on different sub-carriers (where as in CDMA the users are on the same channel). This complicates any attempt to use two eNodeB's to simultaneously serve the same user. The CoMP feature attempts to resolve this through heavy use of the "back channel" infrastructure, by delivering data meant for a given user at the fringe to two eNodeB's which then deliver that data to the user in a coordinated fashion. One significant challenge that prevented this functionality in the original LTE protocol is the fact that the "back channel" infrastructure (an ip based network) tends to have varying and unpredictable delays ("latencies"), making it harder for two eNodeB's to coordinate their simultaneous delivery of that data to the fringe user in a consistent fashion.

> Hetrogeneous Network (Het-Net) – This feature allows eNodeB's to use smaller "micro" or "fempto" cells as "satellite" extensions of itself to effectively fill in any coverage holes or otherwise service small under-served pockets of demand (e.g. around a strip-mall or movie theater complex, etc.). This not only helps provide better coverage in previously under-served areas, in so doing it helps reduce the radio noise in the environment by minimizing the need to crank up power to make the connections between the users and the distant eNodeB's. The result of this feature will be to improve capacity while enhancing overall user throughput.

> Self-Organizing Network (SON) – Sometimes referred to as "smart networks", this feature improves the network's ability to manage interference by enabling multiple eNodeB's to coordinate Resource Block assignments delivered to users at the cell edge. Under this feature, for example, eNodeB_7 avoids using certain Resource Blocks during the time its neighber eNodeB_11 uses those blocks to send data to a user at the fringe (thus reducing the noise on those blocks at that moment, and thereby improving the fringe user's ability to correctly receive its data, and thus reduce re-sends).

> Dual layer Beamforming – This feature attempts to realize something of the "holy grail" in cellular operations, namely the creation of a dedicated "spot beam" aimed directly at a specific user or cluster of users as they move through an area. Though this has been tried in previous generations (and in military applications with some success), it typically has required very large and complex antenna arrays capable of being electrically steered on a milli-second level. Such implementations not only complicate the eNodeB's antenna array, but also the electronics, software, and processing power needed to make it all work (with MIMO no less). The advantage of beam forming/steering is that if it can be achieved on a wide-scale basis, it would not only help reduce noise on the radio channel, but also increase capacity (by

effectively turning each dedicated beam into each user's own private cell footprint). Complexity and cost are the two (giant) hurdles confronting this solution.

> 8 x 8 MIMO – Following the idea that "if a little is good, a lot must be great" 8 x 8 MIMO looks to further improve throughput by expanding upon the existing protocol's ability to use 2 x 2 and 4 x 4 MIMO (see discussion above). The complications involved in these higher order MIMO schemes, includes the significantly higher level of complexity involved in managing and coordinating all the various MIMO antennas and paths in a 4 x 4 and 8 x 8 MIMO path array. In addition, for MIMO to achieve unique RF paths through the environment, each of the antennas involved need to be separated from the others by roughly a half wavelength or more. Small handheld phones are barely big enough to accommodate the two antennas involved in 2 x 2 MIMO, let alone 4 x 4 or 8 x 8. Laptops on the other hand, might be able to facilitate 4 x 4, but 8 x 8 would be tough (i.e. without requiring the user to wear a special *tin foil hat* equipped with a tiny antenna farm of its own). Machine-to-machine applications on the other hand could work, but most of those (e.g. coke machines, road sensors, etc.) typically do not send huge volumes of data sufficient to make their use of 8 x 8 MIMO of any significant impact in those cases.

Conclusions:

So, *very simply* that's how it all works (well, plus a "few" other minor little details we glossed over for simplicity). When you realize that to perform all of these complex operations, your cell phone typically completes roughly a *million* computational operations *per second* to make this all work seamlessly and transparently for you the end user – through a spaghetti maze of constantly changing multi-path reflections and a *completely* RF polluted environment, on a mirocsecond-by-microsecond basis no less – its a wonder any of this ever works at all.

Equally as amazing is the fact that the typical cell phone now cost you well less than *half* what you paid for your TRS-80 back in 1982, and yet comes complete with dual-core giga-Hertz processors, a *bazillion* times more memory than your KayPro-II and Coleco Vision *combined*, a 24+ channel assisted GPS receiver, a 5+ megapixel high resolution CCD camera, an ultra-high resolution *color* touch screen display, (etc.), complete with far more processing power than all the Mercury, Apollo, Soyuz and SkyLab Space vehicles *combined*, and yet is smaller than your average deck of cards, weighing typically less than 6 ounces – not to mention offering software that can answer virtually *any* question you can pose, and perform virtually *any* task you need but wipe your nose ...

And yet when you drive through the *middle of nowhere,* and the signal coming from the cell site at the absolute last *fringe* of "civilization" near the edge of the trailer park just west of the county land fill *30 miles away* finally starts to fade into the sunset, you inevitably curse "*that damn cell phone*" as it pukes out its guts trying to make that one last desperate gasp for a connection, even as you contemplate hucking it under the wheels of the logging truck behind you (that has been riding your rear bumper since you left the trailer park) in disgust...

Just ask yourself: What would Clark Griswald think of you now. After all, in addition to all of the above, it's also semi-permeable, and yet totally non-osmotic.