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AN INTRODUCTION TO LTE-ADVANCED: THE REAL 4G

The next generation of cellular technology is emerging faster than expected.

Long-Term Evolution (LTE) is being adopted around the world as the primary cell-phone communications service. Multiple 2G and 3G cellular radio methods are being phased out as carriers build their new LTE networks. It will be years before this expansion is complete, and older radio technologies like GSM and CDMA will coexist with LTE for a while *(see "The Evolution Of LTE," p. 34)*.

LTE is probably the most complex wireless system that has ever been developed. It incorporates features that could not have been economically implemented as recently as a decade ago. Today, with large-scale ICs, LTE can be easily accommodated in basestations and in battery-powered handsets alike. The complexity is a function of the advanced wireless methods used as well as the many options and features that can be implemented.

In the meantime, the next phase of the LTE standards as put forth by the Third Generation Partnership Project (3GPP) is ready to be deployed.[1] Called LTE-Advanced (LTE-A), this significant upgrade to the LTE standard will provide more speed and greater reliability. While LTE-A is still being developed, some LTE-A service could begin late in 2013.

FREQUENCY & BANDWIDTH

LTE operates in some of the existing cellular bands as well as newer bands. Specific bands have been designated for LTE *(see the table)*. Different carriers use different bands depending upon the country of operation and the nature of their spectrum holdings. Most LTE phones use two of these bands, and they aren't the same from carrier to carrier. For instance, Verizon's iPhone 5 uses different bands than AT&T's iPhone 5.

Most of the bands are set up for frequency division duplexing (FDD), which uses two separate bands for uplink and downlink. The spacing between FDD channels in bands 1 through 28 varies considerably depending on carrier spectrum holdings. Bands 33 through 44 are used for time division duplexing (TDD), so the same frequencies are used for both uplink and downlink.

LTE is a broadband wireless technology that uses wide channels to achieve high data rates and accommodate lots of users. The standard is set up to permit bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz. The carrier selects the bandwidth depending on spectrum holdings as well as the type of service to be offered. The 5- and 10-MHz widths are the most common. Some bandwidths cannot be used in different bands.

MODULATION

LTE uses the popular orthogonal frequency division multiplex (OFDM) modulation scheme. It provides the essential spectral efficiency to achieve high data rates but also permits multiple users to share a common channel. OFDM divides a given channel into many narrower subcarriers. The spacing is such that the subcarriers are orthogonal, so they won't interfere with one another despite the lack of guard bands between them. This comes about by having the subcarrier spacing equal to the reciprocal of symbol time. All subcarriers have a complete number of sine wave cycles that upon demodulation will sum to zero.

In LTE, the channel spacing is 15 kHz. The symbol period therefore is 1/15 kHz = 66.7 µs. The high-speed serial data to be transmitted is divided up into multiple slower streams, and each is used to modulate one of the subcarriers. For example, in a 5-MHz channel, up to 333 subcarriers could be used but the actual number is more like 300. A 20-MHz channel might use 1024 carriers. The modulation on each can be quadrature phase-shift keying (QPSK), 16-phase quadrature amplitude modulation (16QAM), or 64-state quadrature amplitude modulation (64QAM) depending on the speed needs.

OFDM uses frequency and time to spread the data, providing high speeds and greater signal reliability *(Fig. 1)*. For each subcarrier, the data is sent in sequential symbols where each symbol represents multiple bits (e.g., QPSK 2 bits, 16QAM 4 bits, and 64QAM 6 bits.) The basic data rate through a 15-kHz subcarrier channel is 15 kbits/s. With higher-level modulation, higher data rates are possible.

Data to be transmitted is allocated to one or more resource blocks (RBs). An RB is a segment of the OFDM spectrum that is 12 subcarriers wide for a total of 180 kHz. There are seven time segments per subcarrier for a duration of 0.5 ms. Data is then transmitted in packets or frames, and a standard frame contains 20 time slots of 0.5 ms each. An RB is the minimum basic building block of a transmission, and most transmissions require many RBs.

The only practical way to implement OFDM, though, is to do it in software. The fast Fourier transform (FFT) handles the basic process. The transmitter uses the inverse FFT, while the receiver uses the FFT. The algorithms are implemented in a digital signal processor (DSP), an FPGA, or an ASIC designed for the process. The usual techniques of scrambling and adding error-correcting codes are implemented as well.

OFDM was chosen for LTE primarily because of its reduced sensitivity to multipath effects. At the higher microwave frequencies, transmitted signals can take multiple paths to the receiver. The direct path is the best and preferred but multiple objects may reflect signals, creating new signals that reach the receiver somewhat later. Depending on the number of reflected signals,

BANDS ALLOCATED SPECIFICALLY FOR LTE

LTE band number	Uplink (MHz)	Downlink (MHz)
1	1920 to 1980	2110 to 2170
2	1850 to 1910	1930 to 1990
3	1710 to 1785	1805 to 1880
4	1710 to 1755	2110 to 2155
5	824 to 849	869 to 894
6	830 to 840	875 to 885
7	2500 to 2570	2620 to 2690
8	880 to 915	925 to 960
9	1749.9 to 1784.9	1844.9 to 1879.9
10	1710 to 1770	2110 to 2170
11	1427.9 to 1452.9	1475.9 to 1500.9
12	698 to 716	728 to 746
13	777 to 787	746 to 756
14	788 to 798	758 to 768
15	1900 to 1920	2600 to 2620
16	2010 to 2025	2585 to 2600
17	704 to 716	734 to 746
18	815 to 830	860 to 875
19	830 to 845	875 to 890
20	832 to 862	791 to 821
21	1447.9 to 1462.9	1495.9 to 1510.9
22	3410 to 3500	3510 to 3600
23	2000 to 2020	2180 to 2200
24	1625.9 to 1660.9	1525 to 1559
25	1850 to 1915	1930 to 1995
26	859 to 894	814 to 849
27	852 to 869	807 to 824
28	758 to 803	703 to 748
33	1900 to 1920	1900 to 1920
34	2010 to 2025	2010 to 2025
35	1850 to 1910	1850 to 1910
36	1930 to 1990	1930 to 1990
37	1910 to 1930	1910 to 1930
38	2570 to 2620	2570 to 2620
39	1880 to 1920	1880 to 1920
40	2300 to 2400	2300 to 2400
41	2496 to 2690	2496 to 2690
42	3400 to 3600	3400 to 3600
43	3600 to 3800	3600 to 3800
44	703 to 803	703 to 803

their strengths, their ranges, and other factors, the signals at the receiver may add up in a destructive way, creating fading or signal dropout.

The multipath effects occur when the signals reach the receiver all within the time for one symbol period. A symbol is a modulation state that is either an amplitude, a phase, or an amplitude-phase combination representing two or more bits. When the multipath effects lead the signals to arrive at the receiver spread over several symbol periods, inter-symbol interference (ISI) occurs, producing bit errors.

These issues can be overcome with error detecting and correcting codes, but these codes add to the complexity of the system. An equalizer at the receiver that collects all the received signals and delays them so they all add can also correct for this problem but only further complicates the process.

Spreading the signals in the form of multiple subcarriers over a wide bandwidth reduces these effects, especially if the symbol rate on each subcarrier is longer as it is in OFDM. If the multipath effects occur in less than one symbol period, no equalizer is needed. Time or frequency shifts such as those that are produced by the Doppler effect in a moving vehicle cause frequency variation of the subcarriers at the receiver. This shift in frequency results in the loss of orthogonality and subsequently bit errors.

LTE mitigates this problem by adding a cyclical prefix (CP) to each transmitted bit sequence. The CP is a portion of an OFDM symbol created during the DSP process that is copied and added back to the front of the symbol. This bit of redundancy allows the receiver to recover the symbol if the time dispersion is shorter than the cyclical prefix. OFDM then can be implemented without the complex equalization that can also correct for this problem.

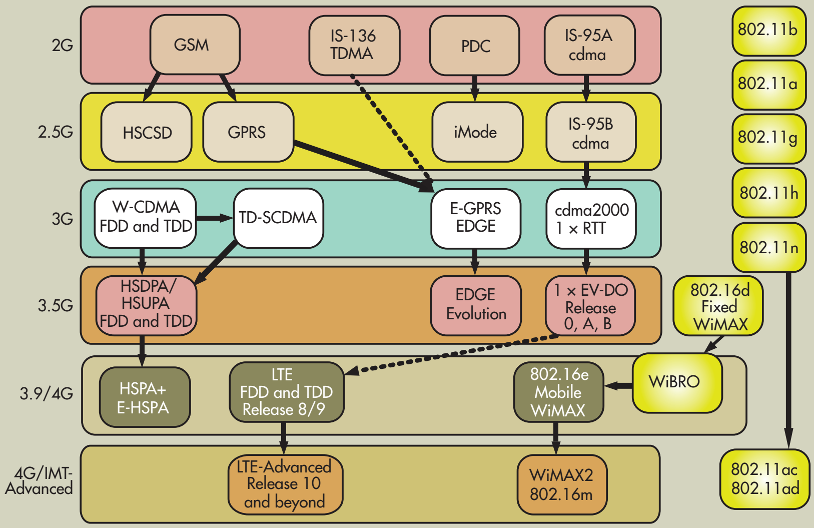
While LTE's downlink uses OFDM, the uplink uses a different modulation scheme known as single-carrier frequency-division multiplexing (SC-FDMA). OFDM signals have a high peak to average power ratio (PAPR), requiring a linear power amplifier with overall low efficiency. This is a poor quality for battery-operated handsets. While complex, SC-FDMA has a

THE EVOLUTION OF LTE

THE THIRD GENERATION Partnership Project (3GPP), the international organization that developed the widely used UMTS WCDMA/HSPA 3G standards, also developed Long-Term Evolution (LTE). Release 8 was completed in 2010, followed by release 9. Available now, release 10 defines the LTE-Advanced (LTE-A) standard.

Multiple cell-phone technologies designated by generations have led to LTE-A (see the figure). The first generation was analog (FM) technology, which is no longer available. The second generation (2G) brought digital technology with its benefits to the industry. Multiple incompatible 2G standards were developed. Only two, GSM and IS-95A CDMA, have survived.

The third generation (3G) standards were created next. Again, multiple standards were developed, notably WCDMA by the 3GPP and cdma2000 by Qualcomm. Both have survived and are still used today. The 3G standards were continually updated into what is known as 3.5G. WCDMA was upgraded to HSPA, and cdma2000 was expanded with 1xRTT EV-DO releases A and B. Both are still widely deployed.



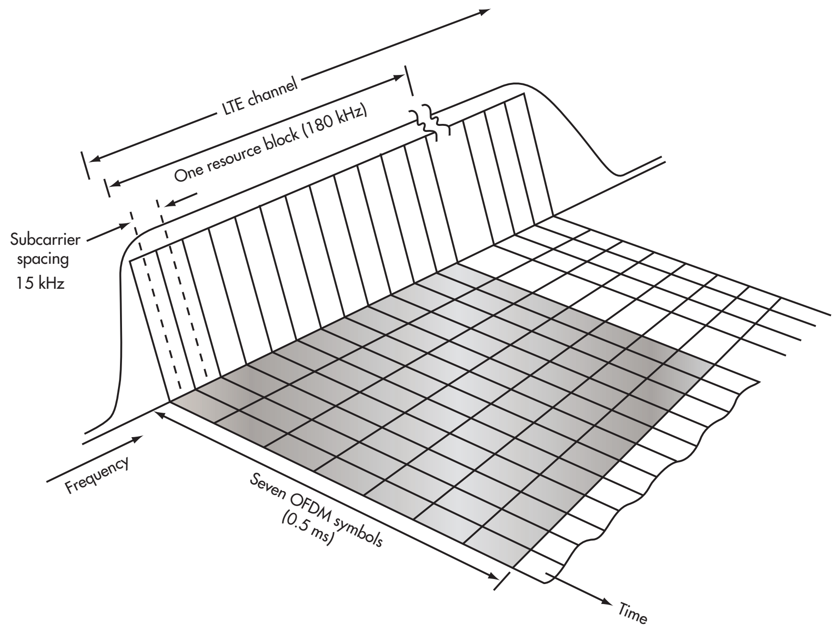
Cellular radio standards really left FM technologies behind in 1990 with 2G standards like GSM and IS-95A cdma. More than 20 years later, we're approaching true 4G with LTE-Advanced.

In fact, in many places around the world, carriers are still adding 3G or upgrading their 3G systems. In the U.S., AT&T and T-Mobile use GSM/WCDMA/HSPA while Verizon, Sprint, and MetroPCS use cdma2000/EV-DO. All of these carriers are building LTE networks.

LTE was created as an upgrade to the 3G standards. The cellular industry recognized its major benefits, and virtually every mobile carrier has embraced it as the next generation. All cellular operators are now on the path to implementing LTE. While 3GPP still defines LTE as a 3.9G technology, all of the current LTE networks are marketed at 4G. The real 4G as designated by 3GPP is LTE-A.

Currently, LTE is alive and functioning in many U.S. cellular companies and in others worldwide. The networks are not fully built out, and most of the older 2G and 3G systems are functioning in parallel. Since LTE coverage is not universal, most cell phones incorporate 2G and 3G systems for voice in areas where LTE is not yet deployed. LTE-A deployment is expected in 2014 and beyond.

LTE brings amazing new capabilities to the cellular business. First, it expands carrier capacity, meaning more subscribers can be added for a given spectrum assignment. Second, it provides the high data rates needed by growing new applications, mainly video downloads to smart phones and other Internet access. Third, it makes cellular connectivity more reliable. All of these needs are important to maintaining growth and profitability in the wireless business.



1. LTE transmits data by dividing it into slower parallel paths that modulate multiple subcarriers in the assigned channel. The data is transmitted in segments of one symbol per segment over each subcarrier.

lower PAPR and is better suited to portable implementation.[2,3]

MIMO

LTE incorporates multiple-input multiple-output (MIMO), which uses two or more antennas and related receive and transmit circuitry to achieve higher speeds within a given channel. One common arrangement is 2x2 MIMO, where the first number indicates the number of transmit antennas and the second number is the number of receive antennas. Standard LTE can accommodate up to a 4x4 arrangement.

MIMO divides the serial data to be transmitted into separate data streams that are then transmitted simultaneously over the same channel. Since each signal path is different, with special processing they can be recognized and separated at the receiver. The result is an increase in the overall data rate by a factor related to the number of antennas. This technique also mitigates the multipath problem and adds to the signal reliability because of the diversity of reception.

The difficultly in implementing MIMO arises because of the small size of the handset and its limited space for antennas. Already, most smart phones include five antennas including those for all the different cellular bands plus Wi-Fi, Bluetooth, GPS, and perhaps near-field communications (NFC). Most phones probably won't feature more than two LTE MIMO antennas, and their inclusion will depend on whether or not they can be spaced far enough apart to preserve spatial diversity with sufficient isolation between them. Of course, it's easier to use more basestation antennas. A typical LTE arrangement appears to be 4x2 to provide optimal coverage with the space available.

DATA RATE

The data rate actually used or achieved with LTE depends on several features: channel bandwidth, modulation type, MIMO configuration, and the quality of the wireless path. In the worst-case situation, data rate could be only a few megahertz. But under good conditions, data rate can rise to more than 300 Mbits/s. On average, most practical LTE downlink rates range from 5 to 15 Mbits/s, which is faster than some fixed Internet access services using cable or DSL.

ACCESS

Access refers to using the same channel to accommodate more than one user. This is effectively a multiplexing method. Standard methods include frequency

2. The Agilent N7109A multi-channel LTE signal analyzer handles up to 8x8 MIMO channels.

division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). GSM uses TDMA by dividing a single channel into multiple time slots. In 2G and 3G CDMA systems, code division uses unique coding for each user with a single bandwidth.

OFDM now offers OFDM Access (OFDMA), which uses some of the available subcarriers and time slots within those subcarriers for each user. The number of subcarriers and time slots used depends on multiple factors. In any case, it's usually possible to accommodate up to hundreds of users per channel bandwidth.

TD-LTE

Most LTE will be of the FDD variety at least in the United States, Europe, and parts of Asia. However, TD-LTE is being widely implemented in China and India because of the nature of their spectrum availability. TD-LTE conserves spectrum and provides for more users per megahertz. The LTE standards include a definition for TD-LTE. Some U.S. carriers will use TD-LTE including Clearwire and Sprint.

LTE-ADVANCED

LTE-A builds on the LTE OFDM/MIMO architecture to further increase data rate. It is defined in 3GPP releases 10 and 11. There are five major features: carrier aggregation, increased MIMO, coordinated multipoint transmission, heterogeneous network (HetNet) support, and relays.

Carrier aggregation combines up to five 20-MHz channels into one to increase data speed. These channels can be contiguous or non-contiguous as defined by the carrier's spectrum assignments. With maximum MIMO assignments, 64QAM, and 100-MHz bandwidth, a peak downlink data rate of 1 Gbit/s is possible.

LTE defines MIMO configurations up to 4x4. LTE-A extends that to 8x8 with support for two transmit antennas in the handset. Most LTE handsets use two receive antennas and one transmit antenna. These MIMO additions provide future data speed increases if adopted.

HetNet support refers to support for small cells in a larger overall heterogeneous network. The HetNet is an amalgamation of standard macrocell basestations plus microcells, metrocells, picocells, femtocells, and even Wi-Fi hotspots. This network increases coverage in a given area to improve connection reliability and increased data rates.

Coordinated multipoint transmission, also known as cooperative MIMO, is a set of techniques using different forms of MIMO and beamforming to improve the performance at cell edges. It uses coordinated scheduling and transmitters and antennas that aren't collocated to provide greater spatial diversity that can improve link reliability and data rate.

Relays use repeater stations to help coverage in selected areas, especially indoors where most calls are initiated. LTE-A defines another basestation type called a relay station. It's not a complete basestation but a type of small cell that will fit in the HetNet infrastructure and provide a way to boost data rates and improve a wireless link's dependability.

Some deployment of LTE-A is expected in late 2013 with increasing adoption in 2014 and beyond. LTE-A is forward and backward compatible with basic LTE, meaning LTE handsets will work on LTE-A networks and LTE-A handsets will work on standard LTE networks.

LTE-A DESIGN CHALLENGES

LTE solves many problems in providing high-speed wireless service. There is no better method, at least for now, but it does pose multiple serious design issues. The greatest problem is the necessity of having to use multiple bands that often are widely spaced from one another. As a result, multiple antennas, multiple power amplifiers, multiple filters, switching circuits, and, sometimes, complex impedance matching solutions are required. Each cellular operator specifies cell phones for its spectrum.

In addition, the power amplifiers (PAs) must be very linear if error vector magnitude (EVM) is to be within specifications for the various multi-level modulation methods used. Linear amplifiers are inefficient and consume the most power in the phone except for the touchscreen. The need to cover multiple bands necessitates the use of multiple PAs. Battery life in an LTE phone is typically shorter as a result. The need to include MIMO also means additional antennas and PAs.

Solutions to these problems lie in fewer yet more efficient PAs. Also, wider-bandwidth antennas solve the multiband problem. Companies like Ethertronics and SkyCross are designing tunable antennas as well to cover multiple bands with a single structure.

Another challenge is test. Several test companies have created systems to test LTE systems with MIMO, which can be a particularly complex process. One of the greatest challenges is testing the higher-level MIMO configurations. LTE-A permits up to 8x8 MIMO. Agilent's N7109A multi-channel MIMO analyzer is designed to work with the company's 89600 vector signal analyzer (VSA) and related Signal Studio software to test LTE-A in all its various configurations *(Fig. 2)*.

VOICE OVER LTE

LTE is a packet-based IP data network. It doesn't include a voice service yet, though one is planned. Today, if you're using an LTE smart phone, you're still using the existing 2G or 3G network for what is called circuit-switched voice service. Voice over LTE (VoLTE) eventually will be implemented. VoLTE is just Voice over Internet Protocol (VoIP) over LTE, and it will operate simply as a data application on the IP network.

While a VoLTE protocol has been defined, implementation requires major engineering decisions and network changes, mostly concerning maintaining voice connections for older non-LTE phones for some extended period. Particularly tricky are the changes that will allow LTE phone users to get voice service if they move into an area that doesn't have LTE.

When VoLTE is available, subscribers could initiate a call using the LTE system but drive out of the LTE coverage area. Systems must be able to hand that call off to a traditional voice network. The mechanism for this, network software called circuit-switched fallback (CSFB), is now available on most networks. Another issue is getting VoLTE into the handsets. VoLTE requires a separate chip in the phone, and few phones have such a capability today.

VoIP also requires a vocoder, a circuit that is essentially an analog-to-digital converter (ADC) to digitize the voice signal and a digital-to-analog converter (DAC) to convert the digital voice back into analog voice for the user. A vocoder also incorporates voice compression, a technique that effectively minimizes the number of bits used to represent voice. Voice then can be transmitted faster but at lower data rates so it doesn't occupy much bandwidth.

LTE uses the Adaptive Multi-Rate (AMR) vocoder, which also is used in GSM systems and other 3GPP standards. It has a variable bit-rate capability from 1.8 to 12.2 kbits/s. Digitized voice is then assembled into AMR packets and then into IP packets that are scheduled into a transmission sequence. A call is allocated to some of the OFDMA subcarriers and to some of the time slots within the bit streams of each subcarrier.

All of the needed phone and network changes will take time, so VoLTE isn't widespread. Carrier MetroPCS has it now on its LTE network and Verizon has VoLTE in trials, as do most other major carriers. However, there will be very little VoLTE activity until 2014 and beyond.

WAITING FOR 5G

It will take a decade or more for LTE and especially LTE-A to dominate cellular coverage. Furthermore, new LTE releases are yet to come. In addition, some provisions of current LTE releases have yet to be implemented, such as self-organizing networks (SONs), which make networks easier to plan, configure, optimize, and manage.

With SON, all basestations would be self-configuring taking into account nearby basestations and using internal algorithms to heal, self-optimize, and adapt to new nearby stations and other conditions. The small-cell movement is definitely LTE-based, and extensive deployment with SON is yet to come. In addition, new higher-frequency spectrum such as 3550 to 3650 MHz will be found, making it possible to extend 4G well into the future.

In the meantime, research continues into the "next big thing," more specifically the fifth generation (5G) of cellular wireless. 5G may simply stay on the same path as 4G and LTE, using higher frequencies and wider bandwidths to achieve even higher data rates. With semiconductor technology still viable at ever-smaller IC feature sizes, operation well into the hundreds of gigahertz is possible.

Already, advanced millimeter wave (30 to 300 GHz) systems are functioning with advanced chipsets in short-range personal-area networks (PANs) for home video transfer (60 GHz), automotive radar (77 GHz), and cellular/hot-spot backhaul (80 GHz). Some experts think the 28-GHz and 38-GHz spectrum segments offer good opportunities for cellular. Because of the higher frequencies, range is shorter, meaning more but smaller cell sites.

However, by using higher-gain antenna arrays and beamforming, coverage will be reliable and the available bandwidth will permit download data rates as high as 10 Gbits/s. It's something to look forward to. ed

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