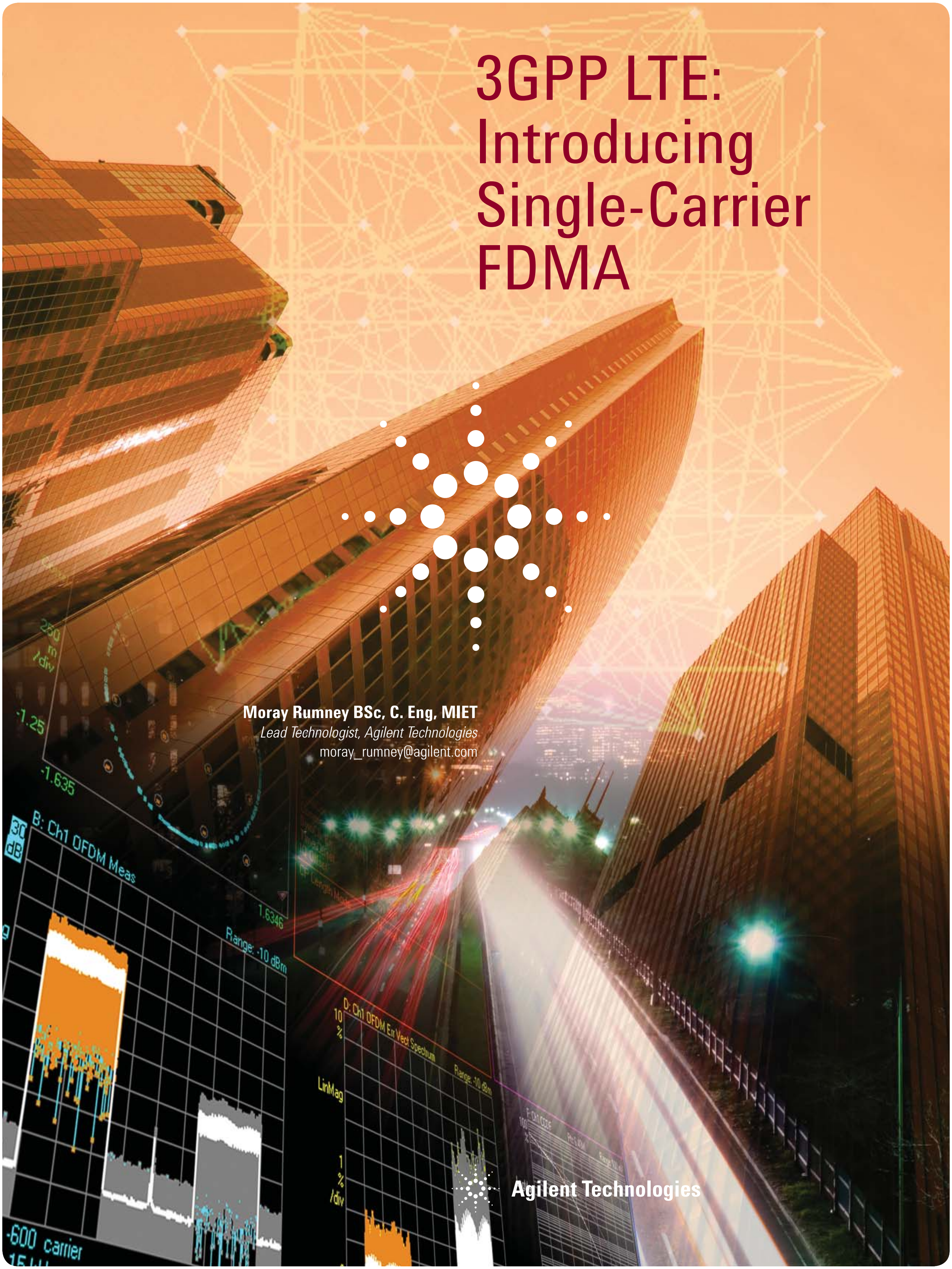
# 3GPP LTE: Introducing Single-Carrier FDMA





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Close on the heels of IEEE's new 802.16e standard—better known as Mobile WiMAX™ — follows the response from the Third-Generation Partnership Project (3GPP) in the form of its Long-Term Evolution (LTE) project. We featured WiMAX™ in Issue Three of *Agilent Measurement Journal* and in this article we explore what LTE aims to bring to the wireless ecosystem. After considering the broader aspects of LTE, we take a closer look at the uplink, which uses a new modulation format called single-carrier frequency-division multiple access (SC-FDMA). These are interesting times because it is rare that the communications industry rolls out a new modulation format.

From both a technical and practical point of view, there is much to understand, examine and evaluate in the capabilities and benefits that SC-FDMA brings to LTE. SC-FDMA is a hybrid modulation scheme that combines the low peak-to-average ratio (PAR) of traditional single-carrier formats such as GSM with the multipath resistance and in-channel frequency scheduling flexibility of orthogonal frequency-division multiplexing (OFDM).

## Acronyms galore: LTE history and context

LTE's study phase began in late 2004. The overall goal was to select technology that would keep 3GPP's Universal Mobile Telecommunications System (UMTS) at the forefront of mobile wireless well into the next decade. Key project objectives were set in the following areas: peak data throughput; spectral efficiency; flexible channel bandwidths; latency; device complexity; and overall system cost. The main decision was whether to pursue the objectives by continuing to evolve the existing W-CDMA air interface (which incorporates HSPA*) or adopt a new air interface based on OFDM. At the conclusion of the study phase, 3GPP decided that the project objectives could not be entirely met by evolving HSPA. As a result, the LTE evolved radio access network (RAN) is based on a completely new OFDM air interface.

*HSPA (high-speed packet access) refers collectively to high-speed downlink packet access (HSDPA) and high-speed uplink packet access (HSUPA), the latter being formally known as the Enhanced Dedicated Channel (E-DCH).

This does not mean the end of 3GPP's interest in GSM and W-CDMA. Rather, the investment in these technologies — and their remaining untapped potential — means that LTE is not the only format being developed in 3GPP Release 8. For example, the EDGE Evolution project will be pushing GSM to newer levels and the HSPA+ project — the runner-up to OFDM for LTE — will continue to evolve the underlying W-CDMA, HSDPA and HSUPA technologies. For an overview of how these formats inter-relate, please see "What Next for Mobile Telephony?" in Issue Three of *Agilent Measurement Journal*.

By using OFDM, LTE is aligning with similar decisions made by 3GPP2 for Ultra-Mobile Broadband (UMB) and by IEEE 802.16 for WiMAX. For an overview of OFDM technology, please see "Understanding the Use of OFDM in IEEE 802.16 (WiMAX)" in Issue Two of *Agilent Measurement Journal*. Although the article explains the basics of OFDM with reference to WiMAX, the general principles apply to LTE and UMB as well.

Within the formal 3GPP specifications, the LTE evolved RAN is split into two parts: the Evolved UMTS Terrestrial Radio Access (E-UTRA) describing the mobile part; and the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) for the base station. For simplicity, this article refers to the new air interface by its project name, LTE. This is becoming common usage just as happened with another project name, UMTS, which has been synonymous with W-CDMA since 1999. In addition to developing LTE, 3GPP is also working on a complementary project known as System Architecture Evolution (SAE), which defines the split between LTE and a new Evolved Packet Core (EPC), which is a flatter packet-only core network that aims to deliver the higher throughput, lower cost and lower latency promised by LTE. The EPC is also designed to provide seamless interworking with existing 3GPP and non-3GPP access technologies.

## LTE objectives and timing

The sidebar *LTE at a glance* (page 25) describes the major objectives of the LTE project and some of the key system attributes. Figure 1 shows an overall timeline for the LTE project. Compared to UMTS, the overall timescale is shorter, due largely to a much smoother standardization process. The development of LTE will avoid the 8000-plus change requests ultimately applied over a four-year period to the "frozen" UMTS Release 99 specifications. The instability and subsequent delays in the UMTS standard led to commercial deployment of a proprietary system in Japan before the worldwide standard was available. It is expected that the surprises and delays of UMTS will be averted with LTE, meaning its introduction should be more predictable and better able to avoid a proprietary launch. The dates in Figure 1 are acknowledged as aggressive and may slip; however, progress is solid and, as UMTS proved, trying to rush the process can be counterproductive.

## OFDM: The choice of next-generation wireless

With LTE joining UMB and WiMAX in choosing OFDM as the underlying modulation technology, it could be argued that there is now little to choose between these cellular systems. Of the five major new cellular systems, only HSPA+ and EDGE Evolution do not use OFDM, a difference clearly driven by the practical need for backwards compatibility with their respective installed bases.

OFDM has been around since the mid 1960s and is now used in a number of non-cellular wireless systems such as Digital Video Broadcast (DVB), Digital Audio Broadcast (DAB), Asymmetric Digital Subscriber Line (ADSL) and some of the 802.11 family of Wi-Fi standards. In contrast, it has taken longer for OFDM to be adopted into cellular standards: It was briefly evaluated in the late 1980s during the early stages of GSM and again a decade later as a candidate technology for UMTS but was not adopted in either case. The primary issue was the processing power needed to perform the fast Fourier transform (FFT) operations at the heart of OFDM. In the '80s and '90s, suitable processors were too expensive and power-hungry for mobile applications. Since then, Moore's Law has come to the rescue for first WiMAX then UMB and now LTE.

## Assessing the advantages of OFDM

The primary advantage of OFDM is its resistance to the damaging effects of multipath delay spread (fading) in the radio channel. Without multipath protection, the symbols in the received signal can overlap in time, leading to inter-symbol interference (ISI). In OFDM systems designed for use in multipath environments, ISI can be avoided by inserting a guard period, known as the cyclic prefix (CP), between each transmitted data symbol. The CP is a copy of the end of the symbol inserted at the beginning. By sampling the received signal at the optimum time, the receiver can avoid all ISI caused by delay spread up to the length of the CP.

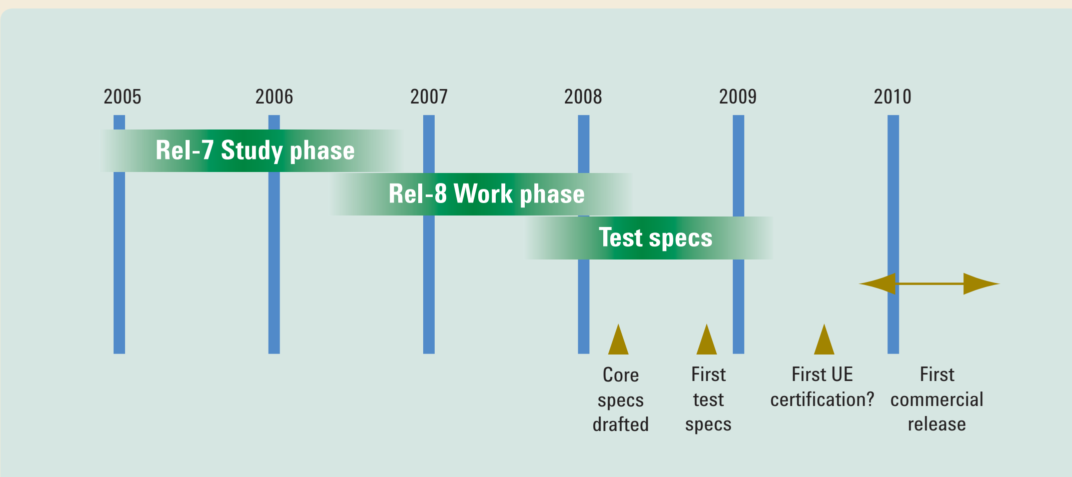


**Figure 1. LTE timing**

The CP is chosen to be slightly longer than the longest expected delay spread in the radio channel. For the cellular LTE system, the standard CP length has been set at 4.69 μs, enabling the system to cope with path delay variations up to about 1.4 km. Note that this figure represents the difference in path length due to reflections, not the size of the cell.* Inserting a CP between every symbol reduces the data handling capacity of the system by the ratio of the CP to the symbol length. For LTE, the symbol length is 66.7 μs, which gives a small but significant seven percent loss of capacity when using the standard CP.

The ideal symbol length in OFDM systems is defined by the reciprocal of the subcarrier spacing and is chosen to be long compared to the expected delay spread. LTE has chosen 15 kHz subcarrier spacing, giving 66.7 μs for the symbol length. In a single-carrier system, the symbol length is closely related to the occupied bandwidth. For example, GSM has 200 kHz channel spacing and a 270.833 ksps symbol rate, giving a 3.69 μs symbol length that is 18 times shorter than that of LTE. In contrast, W-CDMA has 5 MHz channel spacing and a 3.84 Msps symbol rate, producing a 0.26 μs symbol length — 256 times shorter than LTE. It would be impractical to insert a 4.69 μs CP between such short symbols because capacity would drop by more than half with GSM and by a factor of 20 with W-CDMA. Systems that use short symbol lengths compared to the delay spread must rely on receiver-side channel equalizers to recover the original signal.

The link between channel bandwidth and symbol length puts single-carrier systems at a disadvantage versus OFDM when the channel bandwidths get wider. Consider a radio channel with 1 μs of delay spread: A 5 MHz single-carrier signal would experience approximately five symbols of ISI and a 20 MHz signal would experience approximately 20 symbols of ISI. The amount of ISI determines how hard the equalizer has to work and there exists a practical upper limit of about 5 MHz beyond which equalizer costs rise and performance drops off.

Each 15 kHz subcarrier in LTE is capable of transmitting 15 ksps, giving LTE a raw symbol rate of 18 Msps at its 20 MHz system bandwidth (1200 subcarriers, 18 MHz). Using 64QAM — the most complex of the LTE modulation formats — in which one symbol represents six bits, the raw capacity is 108 Mbps. Note that actual peak rates as described in the LTE sidebar are derived by subtracting coding and control overheads and adding gains from features such as spatial multiplexing.

OFDM's other main advantage over single-carrier systems is the ease with which it can adapt to frequency and phase distortions in the received signal, whether caused by transmitter impairments or radio-channel imperfections. Transmitted and received signals are represented in the frequency domain by subcarrier phase and amplitude. By seeding the transmitted signal across the frequency domain with many reference signals (RS, known in other systems as pilots) of predetermined amplitude and phase, the receiver can easily correct for frequency-dependent signal distortions prior to demodulation. This correction is particularly necessary when using higher-order modulation formats (e.g., 16QAM, 64QAM) that are susceptible to erroneous symbol demodulation caused by even small errors in phase and amplitude.

This ability to easily manipulate phase and frequency also lends itself to the processing required for multiple-input/multiple-output (MIMO) antenna techniques such as spatial multiplexing and beamforming. The required manipulations of signal phase and amplitude are much easier to implement in OFDM systems than in single-carrier systems, which represent signals in the time domain.

To summarize the advantages, OFDM systems transmit multiple low-rate subcarriers — resistant to multipath — that combine by the hundreds and thousands to provide a truly scalable system bandwidth and associated data rates. In addition, the frequency-domain representation of signals simplifies the correction of signal errors in the receiver and reduces the complexity of MIMO implementation. By contrast, single-carrier systems do not scale well with bandwidth and are impractical at much above 5 MHz if path delay differences are long.

*Longer CP lengths are available for use in larger cells and for specialist multi-cell broadcast applications. This provides protection for up to 10 km delay spread but with a proportional reduction in the achievable data rates.

## Examining the disadvantages of OFDM

OFDM has two big disadvantages when compared to single-carrier systems. First, as the number of subcarriers increases, the composite time-domain signal starts to look like Gaussian noise, which has a high peak-to-average ratio (PAR) that can cause problems for amplifiers. Allowing the peaks to distort is unacceptable because this causes spectral regrowth in the adjacent channels. Modifying an amplifier to avoid distortion often requires increases in cost, size and power consumption. There exist techniques to limit the peaks (e.g., clipping and tone reservation*) but all have limits and can consume significant processing power while degrading in-channel signal quality.

The other main disadvantage of OFDM systems is caused by tight spacing of subcarriers. To minimize the lost efficiency caused by inserting the CP, it is desirable to have very long symbols, which means closely spaced subcarriers; however, apart from increasing the required processing, close subcarriers start to lose their orthogonality (independence from each other) due to frequency errors. Three key problems associated with close subcarriers cause lost performance. First, any frequency error in the receiver will cause energy from one subcarrier's symbol to interfere with the next. Second, phase noise in the received signal causes similar ISI in the subcarriers but on both sides. Third, Doppler shift can cause havoc. It is easy to remove a fixed Doppler shift but consider the case when multipath is involved and signals are arriving at the receiver from both front and back: The received signals are shifted both higher and lower in frequency and it takes considerable processing power to recover the original signal. To balance the desire for long symbols with the problems caused by close subcarrier spacing, LTE has adopted 15 kHz spacing, with a narrower 7.5 kHz chosen for use with LTE's solution for mobile TV, the evolved Multimedia Broadcast Multicast Service (eMBMS).[1]

*Tone reservation is an advanced form of clipping in which the time-domain signal is shaped such that the error energy falls on specific, reserved in-channel frequencies, ensuring less distortion in the wanted part of the signal.

## Introducing SC-FDMA

The undesirable high PAR of OFDM led 3GPP to choose a different modulation format for the LTE uplink. This difference contributed to the inability of TTA, the Korean standards body, to persuade 3GPP (in 2006) to merge LTE and WiMAX. Pure OFDM is used in the WiMAX uplink but LTE continued to use SC-FDMA, a new hybrid modulation scheme that cleverly combines the low PAR of single-carrier systems with the multipath resistance and flexible subcarrier frequency allocation offered by OFDM.

When a new concept in modulation comes along (e.g., OFDM or CDMA), it can take a long time before the literature starts to make sense. Yet, after everyone "gets it," we often look back at what previously seemed to be impenetrable explanations and wonder what the fuss was about! So it may be with SC-FDMA. The Release 8 3GPP specifications do little to explain the concept. For a formal definition of SC-FDMA, a student of signal processing need look no further than TS 36.211, which gives the mathematical description of the time-domain representation of an SC-FDMA symbol.[2] For the majority of us who find the formal mathematical approach hard to follow, we will present here a graphical comparison of the differences between OFDM and SC-FDMA.

## Comparing OFDM and SC-FDMA

Figure 2 shows how a series of QPSK symbols are mapped into time and frequency by the two different modulation schemes. Rather than using OFDM, we will now shift to the term OFDMA, which stands for orthogonal frequency-division multiple access. OFDMA is simply an elaboration of OFDM used by LTE and other systems that increases system flexibility by multiplexing multiple users onto the same subcarriers. This can benefit the efficient trunking of many low-rate users onto a shared channel as well as enable per-user frequency hopping to mitigate the effects of narrowband fading. For clarity, the example here uses only four (N) subcarriers over two symbol periods with the payload data represented by QPSK modulation. Real LTE signals are allocated in units of 12 adjacent subcarriers (180 kHz) called resource blocks that last for 0.5 ms and usually contain seven symbols whose modulation can be QPSK, 16QAM or 64QAM.

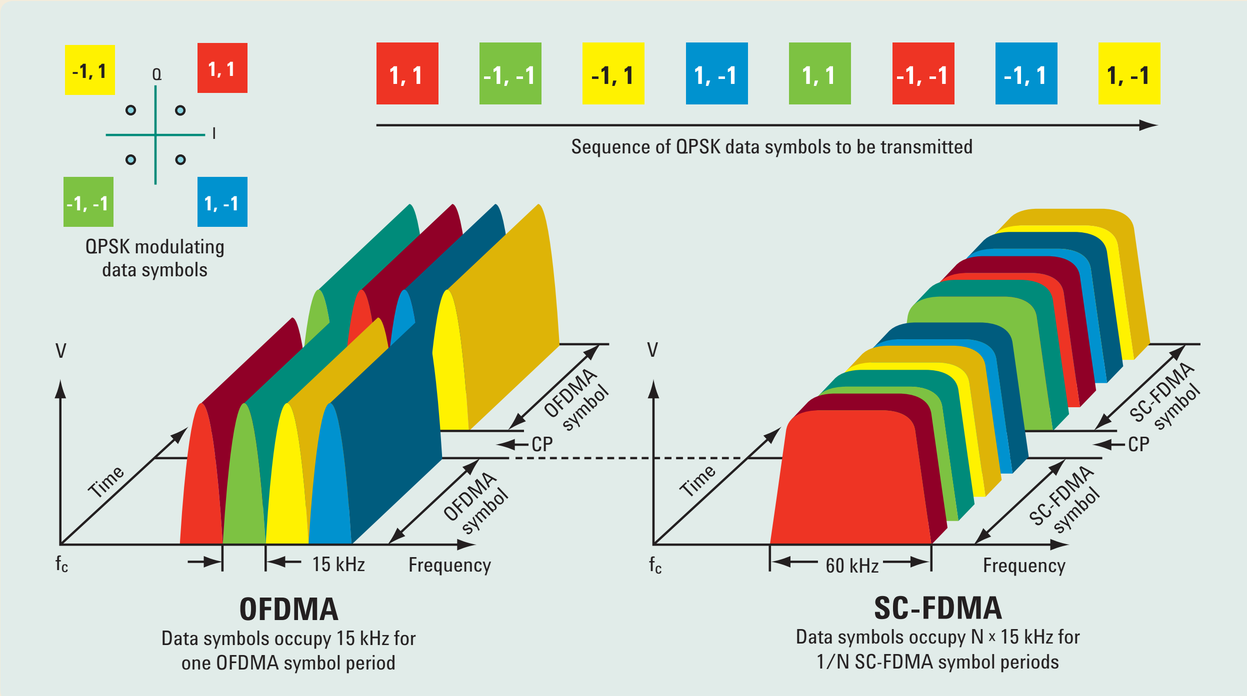


**Figure 2. Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols**

The LTE downlink uses traditional OFDMA methods and differs from other systems such as UMB and WiMAX only in details of the OFDM numerology (that is subcarrier spacing, symbol length, bandwidth, etc.). On the left side of Figure 2, N adjacent 15 kHz subcarriers — already positioned at the desired place in the channel bandwidth — are each modulated for the OFDMA symbol period of 66.7 µs by one QPSK data symbol. In this simple four-subcarrier example, four symbols are taken in parallel. These are QPSK data symbols so only the phase of each subcarrier is modulated and the subcarrier power remains constant between symbols. After one OFDMA symbol period has elapsed, the CP is inserted and the next four symbols are transmitted in parallel. For visual clarity, the CP is shown as a gap; however, it is actually filled with a copy of the end of the next symbol, meaning the transmission power is continuous but has a phase discontinuity at the symbol boundary. To create the transmitted signal, an inverse FFT is performed on each subcarrier to create N time-domain signals that are vector summed to create the final time-domain waveform used for transmission.

SC-FDMA signal generation begins with a special precoding process but then continues as with OFDMA. Before outlining the generation process it is helpful to first describe the end result as shown on the right side of Figure 2. The most obvious difference between the two schemes is that OFDMA transmits the four QPSK data symbols in parallel, one per subcarrier, while SC-FDMA transmits the four QPSK data symbols in series at four times the rate, with each data symbol occupying N × 15 kHz bandwidth. Visually, the OFDMA signal is clearly multi-carrier and the SC-FDMA signal looks more like single-carrier, which explains the "SC" in its name. Note that OFDMA and SC-FDMA symbol lengths are the same at 66.7 µs; however, the SC-FDMA symbol contains N "sub-symbols" that represent the modulating data.

It is the parallel transmission of multiple symbols that creates the undesirable high PAR of OFDMA. By transmitting the N data symbols in series at N times the rate, the SC-FDMA occupied bandwidth is the same as multi-carrier OFDMA but — crucially — the PAR is the same as that used for the original data symbols. This should make heuristic sense without delving into the mathematics: Adding together many narrowband QPSK waveforms in OFDMA will always create higher peaks than would be seen in the wider-bandwidth single-carrier QPSK waveform of SC-FDMA. As the number of subcarriers N increases, the PAR of OFDMA with random modulating data approaches Gaussian noise statistics but, regardless of the value of N, the SC-FDMA PAR remains the same as that used for the original data symbols.

Having seen what SC-FDMA looks like, we will now explain the precoding process that brings it about. Figure 3 shows the first steps, which create a time-domain waveform of the QPSK data sub-symbols. Using the four color-coded QPSK data symbols from Figure 2, the process creates one SC-FDMA symbol in the time domain by computing the trajectory traced by moving from one QPSK data symbol to the next. This is done at N times the rate of the SC-FDMA symbol such that one SC-FDMA symbol contains N consecutive QPSK data symbols. For simplicity, we will not discuss time-domain filtering of the data symbol transitions even though such filtering will be present in any real implementation.

Having created an IQ representation in the time domain of one SC-FDMA symbol, the next stage is to represent it in the frequency domain using a discrete Fourier transform (DFT; Figure 4). The DFT sampling frequency is chosen such that the time-domain waveform of one SC-FDMA symbol is fully represented by N DFT bins spaced 15 kHz apart, with each bin representing one subcarrier with amplitude and phase held constant for 66.7 μs. There is always a one-to-one correlation between the number of data symbols to be transmitted during one SC-FDMA symbol period and the number of DFT bins created — and this in turn becomes the number of occupied subcarriers. This should make intuitive sense: When an increasing number of data symbols is transmitted during one SC-FDMA period, the time-domain waveform changes faster, generating a higher bandwidth and hence requiring more DFT bins to fully represent the signal in the frequency domain.

Note from Figure 4 that there is no longer a direct relationship between the amplitude and phase of the individual DFT bins and the original QPSK data symbols. This is quite different from the OFDMA example in which data symbols directly modulate the subcarriers.

The next stage is to shift the baseband DFT representation of the time-domain SC-FDMA symbol to the desired part of the overall channel bandwidth. Because the signal is now represented as a DFT, frequency shifting is a very simple process achieved by copying the N bins into a larger DFT space that can be up to the size of the system channel bandwidth — of which there are six to choose from in LTE, spanning 1.4 MHz to 20 MHz. The elegance of the DFT lets us position the signal anywhere in the channel bandwidth, thus executing the frequency-division multiple access (FDMA) essential for efficiently sharing the uplink between multiple users. *This explains the origin of the latter portion of "SC-FDMA."

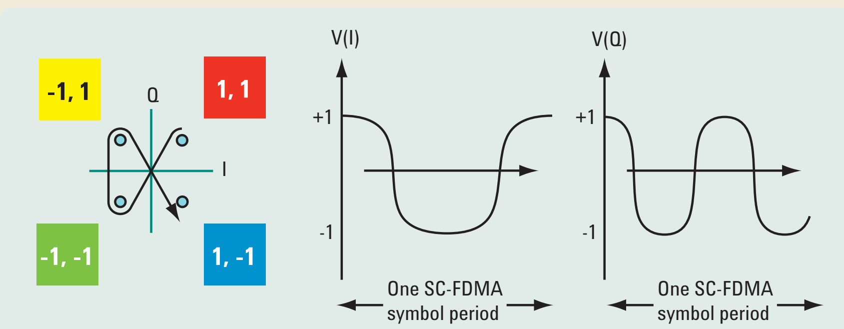


**Figure 3. Creating the time-domain waveform of an SC-FDMA symbol**

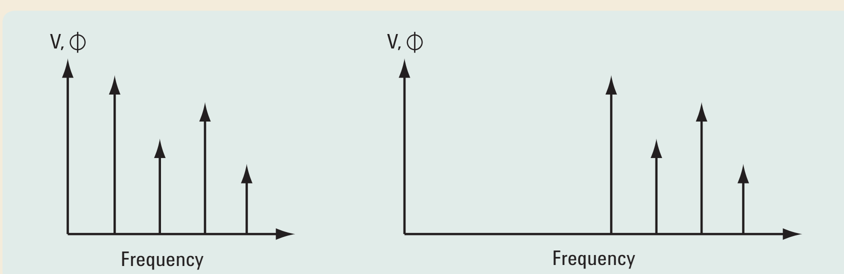


**Figure 4. Baseband and shifted frequency domain representations of an SC-FDMA symbol**

*Although 3GPP did consider a distributed form of subcarrier allocation for the uplink that would have alleviated susceptibility to narrowband fading, it instead opted for the adjacent allocation described here combined with the possibility of frequency hopping at the slot (0.5 ms) level.

To conclude SC-FDMA signal generation, the process follows the same steps as for OFDMA. Performing an inverse FFT converts the frequency-shifted signal to the time domain and inserting the CP provides OFDMA's fundamental robustness against multipath.

If we now return to Figure 2's representation of OFDMA and SC-FDMA, we can consider how each signal would look depending on the analysis bandwidth. Table 1 summarizes the differences between the modulation formats.

When analyzed one subcarrier at a time, OFDMA resembles the original data symbols. At full bandwidth, however, the signal looks like Gaussian noise in terms of its PAR statistics and the constellation. The opposite is true for SC-FDMA. Its relationship to the original data symbols is evident when analyzing the entire signal bandwidth whereupon the constellation (and hence low PAR) of the original data symbols can be observed rotating at N times the SC-FDMA symbol rate (ignoring the seven percent rate reduction due to adding the CP). When analyzed at the subcarrier bandwidth, the SC-FDMA PAR and constellation are meaningless because these are N times narrower than the information bandwidth of the data symbols.

**Table 1. Analysis of OFDMA and SC-FDMA at different bandwidths**

| Modulation format | OFDMA | | SC-FDMA | |
|---|---|---|---|---|
| **Analysis bandwidth** | 15 kHz | Signal BW (N x 15 kHz) | 15 kHz | Signal BW (N x 15 kHz) |
| **Peak-to-average power ratio** | Same as data symbol | High PAR (Gaussian) | Not meaningful (< data symbol) | Same as data symbol |
| **Observable IQ constellation** | Same as data symbol at 66.7 µs rate | Not meaningful (Gaussian) | Not meaningful (< data symbol) | Same as data symbol at N x 66.7 µs rate |

# LTE at a glance

## November 2004 LTE/SAE High-level requirements

- Reduced cost per bit
- More lower-cost services with better user experience
- Flexible use of new and existing frequency bands
- Simplified lower-cost network with open interfaces
- Reduced terminal complexity and reasonable power consumption

## Speed

**Downlink peak data rates (64QAM)**

| Antenna configuration | SISO | 2x2 MIMO | 4x4 MIMO |
|---|---|---|---|
| Peak data rate (Mbps) | 100 | 172.8 | 326.4 |

**Uplink peak data rates (single antenna)**

| Modulation depth | QPSK | 16QAM | 64QAM |
|---|---|---|---|
| Peak data rate (Mbps) | 50 | 57.6 | 86.4 |

## Services

Packet-switched voice and data. No circuit-switched services supported.

## Flexible channel bandwidths

| Bandwidth MHz | Access mode |
|---|---|
| 1.4 | FDD and TDD |
| 3 | FDD and TDD |
| 5 | FDD and TDD |
| 10 | FDD and TDD |
| 15 | FDD and TDD |
| 20 | FDD and TDD |

The 1.6 MHz and 3.2 MHz TDD bandwidths have recently been deleted, and the six remaining bandwidths apply to both FDD and TDD.

## Mobility

Optimized: 0 to 15 km/h
High performance: 15 to 120 km/h
Functional: 120 to 350 km/h
Under consideration: 350 to 500 km/h

## Spectral Efficiency

3-4x Rel-6 HSDPA (downlink)
2-3x Rel-6 HSUPA (uplink)

## Latency

Idle to active < 100 ms
Small packets < 5 ms

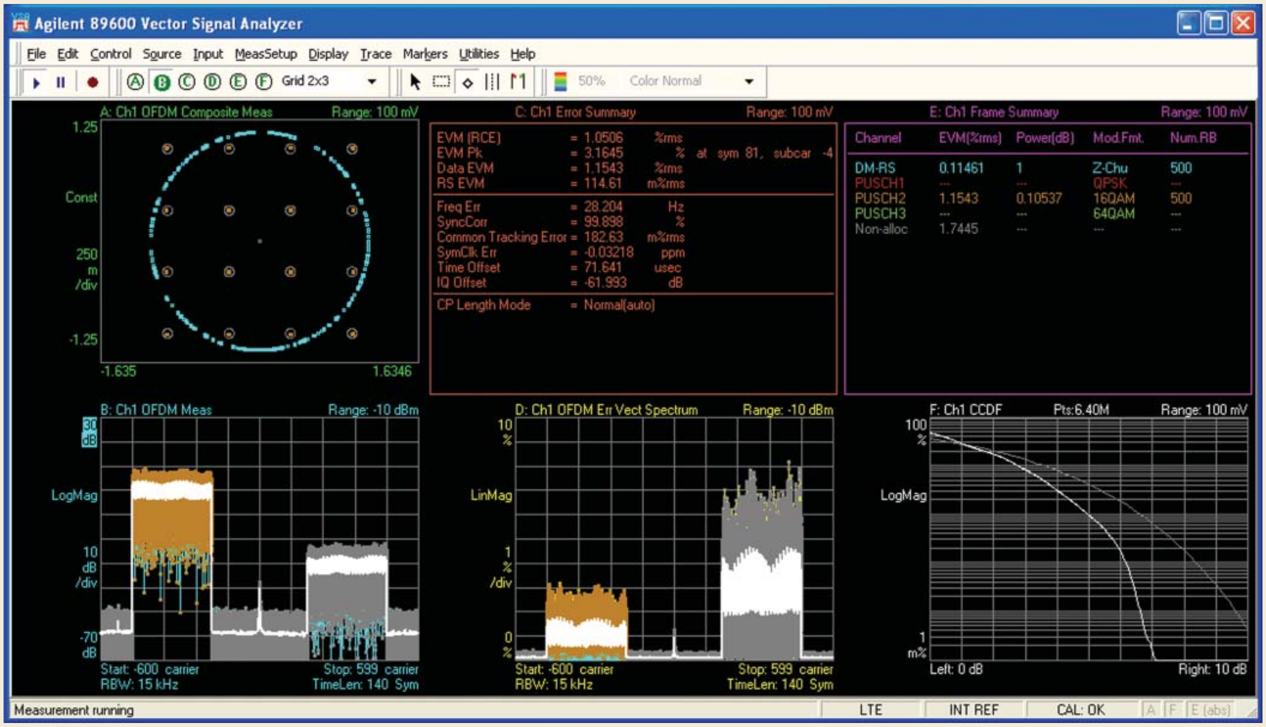


**Figure 5. Analysis of a 16QAM SC-FDMA signal**

## Multipath resistance with short data symbols?

At this point it is reasonable to ask, "How can SC-FDMA still be resistant to multipath when the data symbols are still short?" In OFDMA, the modulating data symbols are constant over the 66.7 μs OFDMA symbol period but an SC-FDMA symbol is not constant over time since it contains N sub-symbols of much shorter duration. The multipath resistance of the OFDMA demodulation process seems to rely on the long data symbols that map directly onto the subcarriers. Fortunately, it is the constant nature of each subcarrier — not the data symbols — that provides the resistance to delay spread. As shown earlier, the DFT of the time-varying SC-FDMA symbol generated a set of DFT bins constant in time during the SC-FDMA symbol period even though the modulating data symbols varied over the same period. It is inherent to the DFT process that the time-varying SC-FDMA symbol — made of N serial data symbols — is represented in the frequency domain by N time-invariant subcarriers. Thus, even SC-FDMA with its short data symbols benefits from multipath protection.

It may seem counterintuitive that N time-invariant DFT bins can fully represent a time-varying signal. However, the DFT principle is simply illustrated by considering the sum of two fixed sine waves at different frequencies: The result is a non-sinusoidal time-varying signal — fully represented by two fixed sine waves.

## Examining a real SC-FDMA signal

Figure 5 shows some of the measurements that can be made on a typical SC-FDMA signal. The constellation in trace A (top left) shows this is a 16QAM signal. The unity circle represents the RS (every seventh symbol), which do not use SC-FDMA but are phase modulated using an orthogonal Zadoff-Chu sequence.[3] Trace B (lower left) shows the signal power versus frequency. The frequency scale is in 15 kHz subcarriers numbered from –600 to 599, which represents a bandwidth of 18 MHz. From this we can conclude this must be a 20 MHz channel and the allocated signal bandwidth is 5 MHz towards the lower end. The brown dots represent the instantaneous subcarrier amplitude and the white dots the average over 10 ms. In the center of the trace, the spike represents the LO leakage (IQ offset) of the signal; the large image to the right is an OFDM artifact deliberately created using 0.5 dB IQ gain imbalance in the signal. Both the LO leakage and the power in non-allocated subcarriers will be limited by the 3GPP specifications.

Trace C (top middle) shows a summary of the measured impairments including the error vector magnitude (EVM), frequency error and IQ offset. Note the data EVM at 1.15 percent is much higher than the RS EVM at 0.114 percent. This is due to a +0.1 dB boost in the data power as reported in trace E, which was ignored (for illustration) by the receiver to create data-specific EVM. Also note the RS power boost is reported as +1 dB, which can also be observed in the IQ constellation because the unity circle does not pass through eight of the 16QAM points. Trace D (lower middle) shows the distribution of EVM by subcarrier. The average and peak of the allocated signal EVM is in line with the numbers in trace C. The EVM for the non-allocated subcarriers reads much higher although the way this in-channel impairment will be specified will be as a power ratio between the wanted signal and the unwanted signal. The ratio for this signal is around 30 dB as can be seen in trace B. The blue dots in trace D also show the EVM of the RS, which is very low.

Trace E (top right) shows the ability to measure EVM by modulation type from one capture. This signal uses only the RS phase modulation and 16QAM so the QPSK and 64QAM results are blank. Finally, trace F (lower right) shows the PAR — the whole point of SC-FDMA — in the form of a complementary cumulative distribution function (CCDF) measurement. It is not possible to come up with a single figure of merit for the PAR advantage of SC-FDMA over OFDMA because it depends on the data rate. The PAR of OFDMA is always higher than SC-FDMA even for narrow frequency allocations; however, when data rates rise and the frequency allocation gets wider, the SC-FDMA PAR remains constant but OFDMA gets worse and approaches Gaussian noise. A 5 MHz OFDMA 16QAM signal would look very much like Gaussian noise. From the white trace it can be seen at 0.01 percent probability the SC-FDMA signal is 3 dB better than the Gaussian reference trace, and as every amplifier designer knows, even a tenth of a decibel shaved from the peak power budget is money in the bank.

## Conclusion

In essence, SC-FDMA means “create a single-carrier waveform and shift it to the desired part of the frequency domain.” After a careful consideration of the characteristics of OFDMA and the new SC-FDMA, we can conclude that SC-FDMA provides the advantages of OFDMA — especially robust resistance to multipath — without the problem of high PAR. The use of SC-FDMA in LTE, however, is restricted to the uplink because the increased time-domain processing would be a considerable burden on the base station, which has to manage the dynamics of multi-user transmission.

It will be interesting to see if LTE — the latest of the three new OFDMA cellular standards — has indeed identified a superior solution for the uplink or whether the pure OFDMA used in WiMAX or the OFDMA/CDMA combination used in UMB prove to be just as successful when all the factors are taken into account. Today, the experts disagree so we will have to wait on the ultimate arbiter, time, before we find out for sure.

**References**

1. 3GPP TS 36.201 v8.0.0 section 4.2.1
2. 3GPP TS 36.211 v8.0.0 subclause 5.6
3. 3GPP TS 36.211 v8.0.0 subclause 5.5



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