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De-mystifying Single Carrier FDMA
The New LTE Uplink

Third-generation wireless communication systems based on W-CDMA (wideband code-division multiple access) are being deployed all over the world. To ensure that these systems remain competitive, the 3GPP (3rd Generation Partnership Project) initiated a project in late 2004 for the long-term evolution (LTE) of 3GPP cellular technology.

This article focuses on the physical layer ("Layer 1") characteristics of the LTE uplink, describing the new Single-Carrier Frequency Division Multiple Access (SC-FDMA) transmission scheme and some of the measurements associated with it. Understanding the details of this new transmission scheme and measurements is a vital step towards developing LTE UE designs and getting them to market.

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The LTE specifications are being documented in Release 8 of the 3GPP standard. The core specifications are scheduled to be completed by mid-2008 with the conformance test specifications following approximately six months later.

With early system deployment expected in the 2010 timeframe, LTE provides a framework for an evolved 3G network, and aims specifically to achieve the following:

- Increased uplink peak data rates up to 86.4 Mbps in a 20 MHz bandwidth with 64QAM (quadrature amplitude modulation)
- Increased downlink peak data rates up to 172.8 Mbps in a 20 MHz bandwidth with 64QAM and 2x2 SU-MIMO (single-user multiple input/multiple output)
- Maximum downlink peak data rates up to 326.4 Mbps using 4x4 SU-MIMO
- Spectrum flexibility with scalable uplink and downlink channel bandwidths from 1.4 MHz up to 20 MHz
- Improved spectral efficiency, with a 2-4 times improvement over Release 6 HSPA (high speed packet access)
- Sub-5 ms latency for small IP (internet protocol) packets
- Mobility optimized for low mobile speed from 0 to 15 km/h; higher mobile speeds up to 120 km/h will be supported with high performance with the system operating up to 350 km/h
- Co-existence with legacy systems while evolving towards an all-IP network

The LTE Air Interface

There are two primary duplexing modes used in LTE which are frequency division duplex (FDD) and time division duplex (TDD). Variants including half-rate FDD are also anticipated. The integration of the FDD and TDD modes of LTE is much closer than was the case with UMTS. The downlink transmission scheme is based on orthogonal frequency division multiplexing (OFDM) and the uplink uses a new transmission scheme called SC-FDMA. This new scheme borrows from both traditional single-carrier schemes as well as from OFDM.

OFDM and OFDMA

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. OFDM's adoption into mobile wireless has been delayed for two main reasons. The first is the sheer processing power which is required to perform the necessary FFT operations. However, the continuing advance of signal processing technology means that this is no longer a reason to avoid OFDM, and it now forms the basis of the LTE downlink. The other reason OFDM has been avoided in mobile systems is the very high peak to average ratio (PAR) signals it creates due to the parallel transmission of many hundreds of closely-spaced subcarriers. For mobile devices this high PAR is problematic for both power amplifier design and battery consumption, and it is this concern which led 3GPP to develop the new SC-FDMA transmission scheme.

Multiple access in the LTE downlink is achieved by using an elaboration of pure OFDM called orthogonal frequency division multiple access (OFDMA). This method allows subcarriers to be allocated to different users. This facilitates the trunking of many lower-rate users as well as enabling the use of frequency hopping to mitigate the effects of narrowband fading.

SC-FDMA

SC-FDMA is a hybrid transmission scheme which combines the low PAR characteristics of single-carrier transmission systems - such as those used for GSM and CDMA - with the long symbol time and flexible frequency allocation of OFDM. The principles behind SC-

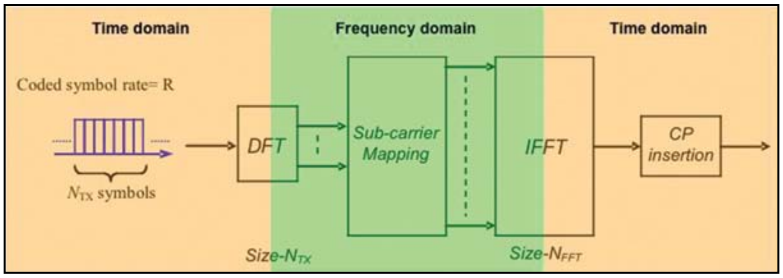

Figure 1 *SC-FDMA signal generation*

FDMA signal generation are shown in Figure 1. This is taken from Figure 1 of the study phase report for the LTE physical layer 3GPP TR 25.814.

On the left hand side of Figure 1 the data symbols are depicted in the time domain. The symbols are converted to the frequency domain using an FFT, and then in the frequency domain they are mapped to the desired location in the overall carrier bandwidth. They must then be converted back to the time domain in order to have the cyclic prefix inserted prior to transmission. An alternative name for SC-FDMA is Discrete Fourier Transform Spread OFDM (DFT-SOFDM).

An alternative description is provided in Figure 2 which shows, in frequency and time, how OFDMA and SC-FDMA would each transmit a sequence of 8 QPSK data symbols. For this simplified example, the number of subcarriers (M) is set to four. For OFDMA, four (M) symbols are taken in parallel, each of them modulating its own subcarrier at the appropriate QPSK phase. Each data symbol occupies 15 kHz for the period of one OFDMA symbol which lasts for 66.7μs. At the start of the next OFDMA symbol, the guard interval containing the cyclic prefix (CP) is inserted. The CP is a copy of the end of a symbol prepended to the start of the symbol. Due to the parallel transmission, the data symbols are the same length as the OFDMA symbols.

In the SC-FDMA case, the data symbols are transmitted sequentially. Since this example involves four subcarriers, four data symbols are transmitted sequentially in one SC-FDMA symbol period. The SC-FDMA symbol period is the same length as the OFDMA symbol at 66.7μs but due to sequential transmission, the data symbols are shorter being 66.7/M μs. A consequence of the higher data rate symbols means more bandwidth is required, so each data symbol occupies 60 kHz of spectrum rather than the 15 kHz for the slower data symbols used for OFDMA. After the four data symbols have been transmitted, the CP is inserted.

Following this graphical comparison of OFDMA and SC-FDMA, the detail of the SC-FDMA signal generation process is shown in Figures 3 and 4. A time domain representation of the data symbol sequence is first generated as shown in Figure 3.

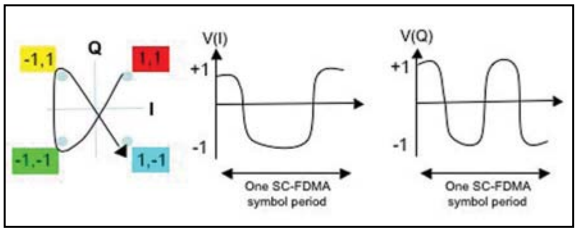

Figure 3 *Creating the time-domain waveform of an SC-FDMA symbol*

For this four subcarrier example a sequence of four data symbols is required to generate one SC-FDMA symbol. Using the first four of the 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 M times the rate of the SC-FDMA symbol such that one SC-FDMA symbol contains M 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 this 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 M DFT bins spaced 15 kHz apart, where each bin represents one subcarrier with amplitude and phase held

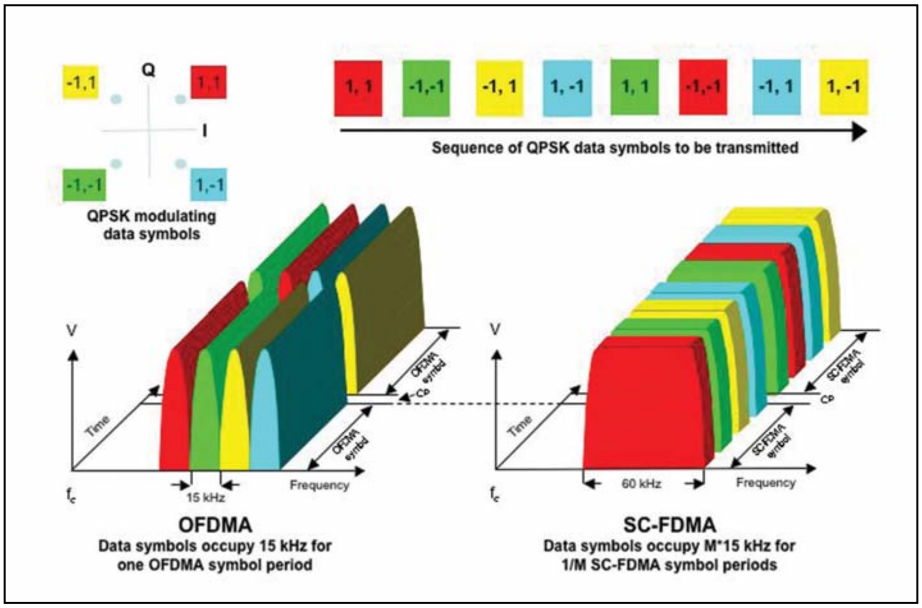

Figure 2 *Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols*

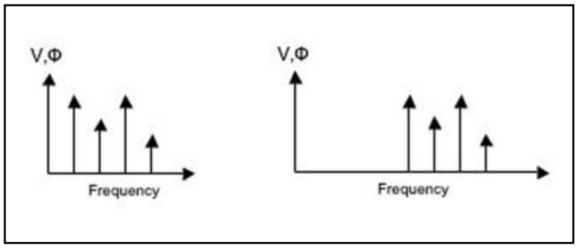

Figure 4. *Baseband and shifted frequency domain representations of an SC-FDMA symbol*

constant for the 66.7μs SC-FDMA symbol period. 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 — which in turn becomes the number of occupied subcarriers. When an increasing number of data symbols are 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.

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 M data 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 M serial data symbols - is represented in the frequency domain by M time-invariant subcarriers. Thus, even SC-FDMA with its short data symbols benefits from multipath protection. Figure 2 shows the SC-FDMA subcarriers all at the same amplitude but in reality each will have its own amplitude and phase for any one SC-FDMA symbol period.

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.

Figure 5 shows the close relationship between SC-FDMA and OFDMA. The orange blocks represent OFDMA processing and the blue blocks represent the additional time domain processing required for SC-FDMA.

UL Signals	**Full Name**	**Purpose**
DMRS	(Demodulation) Reference Signal	Used by the base station for synchronization to the UE and for UL channel estimation. Associated with PUCCH or PUSCH
SRS	Sounding Reference Signal	Used for channel estimation when there is no PUCCH or PUSCH
UL Channels	**Full name**	**Purpose**
PRACH	Physical Randon Access Channel	Call setup
PUCCH	Physical Uplink Control Channel	Scheduling, ACK/NACK
PUSCH	Physical Uplink Shared Channel	Payload

Table 1 *Uplink signals and channels*

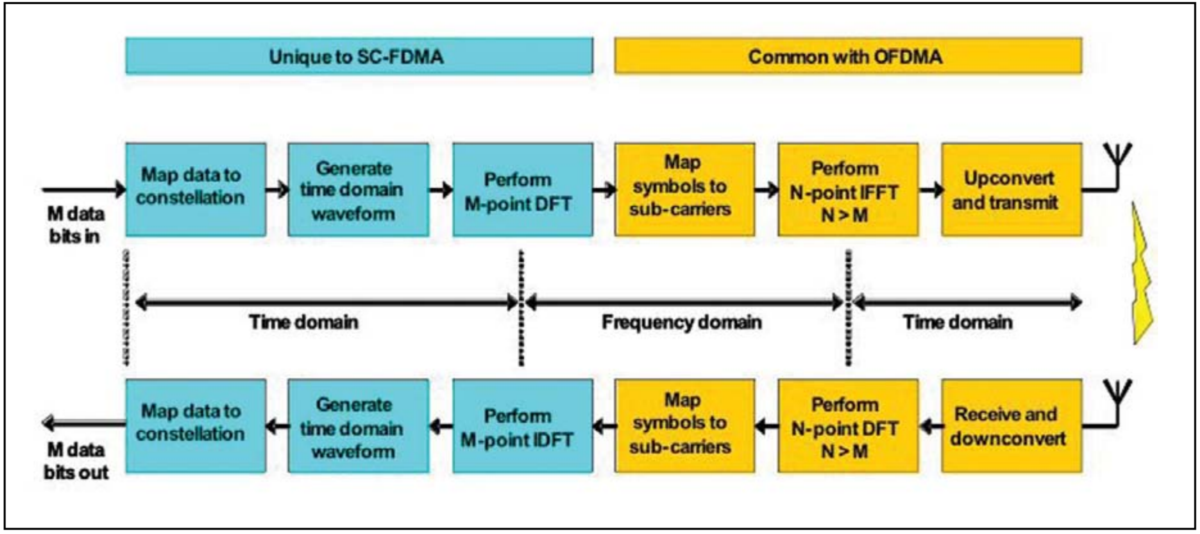

Figure 5 *Simplified model of SC-FDMA generation and reception*

The key point to note is that the signal which is converted from the frequency domain back to the time domain is no more than a frequency shifted version of a series of QPSK symbols. This example illustrates the main reason SC-FDMA was developed: that is, the PAR of the final signal is no worse than that of the original data symbols, which in this case was QPSK. This is very different to OFDMA where the parallel transmission of the same QPSK data symbols creates statistical peaks - much like Gaussian noise - far in excess of the PAR of the data symbols themselves. Limiting PAR using SC-FDMA significantly reduces the need for the mobile device to handle high peak power. This lowers costs and reduces battery drain.

Physical Layer Structure

The LTE physical layer comprises two types of signals known as physical signals and physical channels. Physical signals are generated in Layer 1 and used for system synchronization, cell identification, and radio channel estimation. Physical channels carry data from higher layers including control, scheduling, and user payload. Table 1 shows the uplink physical signals and channels.

Uplink Frame Structure

There are two uplink frame structures, one for FDD operation called type 1 and the other for FDD operation called type 2. Frame structure type 1 is 10 ms long and consists of ten subframes, each

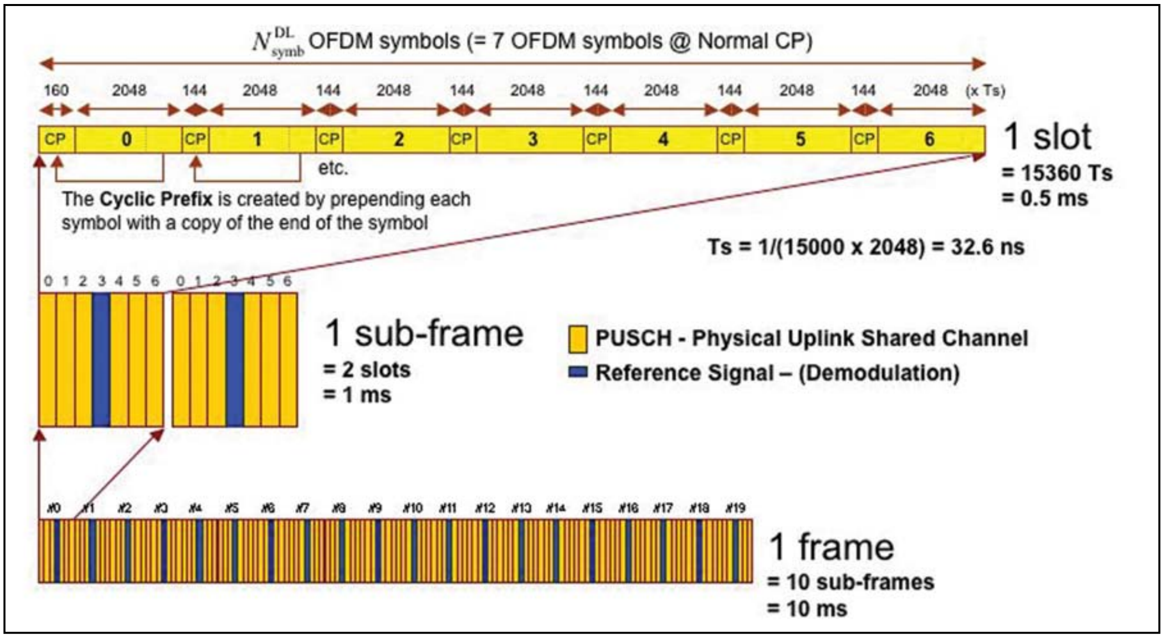

Figure 6 *Frame Structure 1 for uplink showing mapping for DMRS and PUSCH*

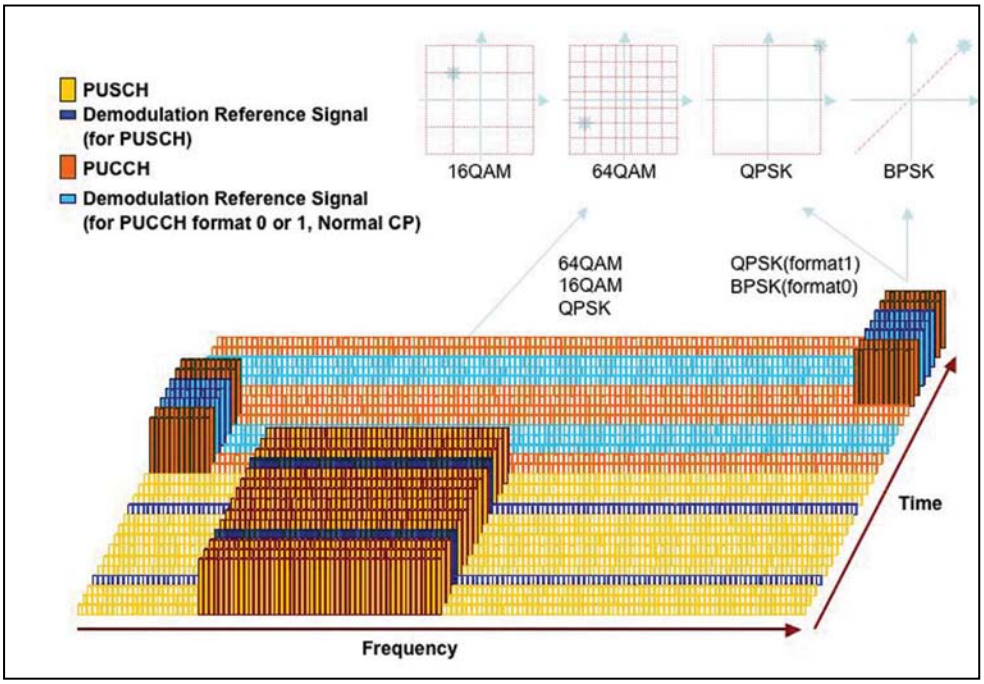

Figure 7 *Frame Structure 1 for the uplink showing one subframe vs. frequency*

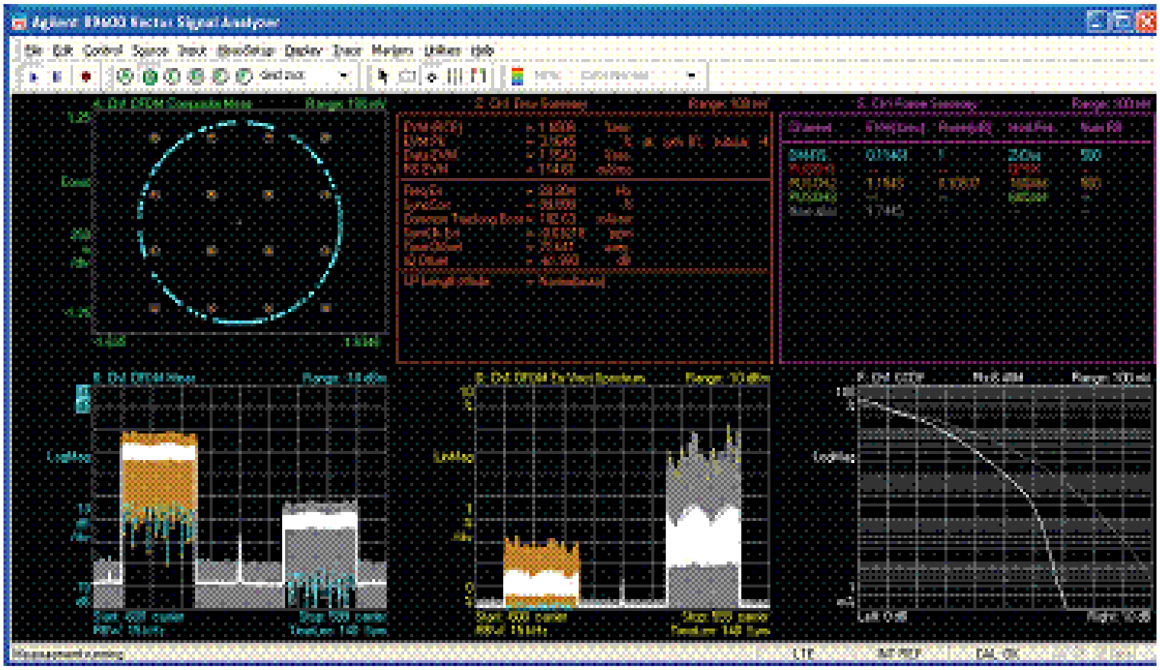

Figure 8 *Analysis of a 16QAM SC-FDMA signal*

comprising two 0.5 ms slots. Figure 6 shows how the DMRS and PUSCH map onto the frame structure. The number of symbols in a slot depends on the CP length. For a normal CP, there are seven SC-FDMA symbols per slot. For an extended CP used for when the delay spread is large, there are six SC-FDMA symbols per slot.

Demodulation reference signals are transmitted in the fourth symbol (that is, symbol number 3) of every slot. The PUSCH can be transmitted in any other symbol.

Figure 7 shows the uplink frame structure type 1 in both frequency and time. Each vertical bar represents one subcarrier. Transmissions are allocated in units called resource blocks (RB) comprising 12 adjacent subcarriers for a period of 0.5 ms. In addition to the DMRS and PUSCH the figure also shows the PUCCH which is always allocated to the edge RB of the channel bandwidth alternating from low to high frequency on adjacent slots. Note that the frequency allocation for one UE is typically less than the system bandwidth. This is because the number of RB allocated directly scales to the transmitted data rate which may not always be the maximum. The DMRS is only transmitted within the PUSCH and PUCCH frequency allocation-unlike the reference signals on the downlink which are always transmitted across the entire channel bandwidth even if the channel is not fully occupied.

If the base station needs to estimate the uplink channel conditions when no control or payload data is scheduled then it will allocate the SRS which is independent of the PUSCH and PUCCH. The PUSCH can be modulated at QPSK, 16QAM or 64QAM. The PUCCH is only QPSK and the DMRS is BPSK with a 45 degree rotation.

Analyzing an SC-FDMA Signal

Figure 8 shows some of the measurements that can be made on a typical SC-FDMA signal using the Agilent 89601A Vector Signal Analyzer software. The IQ constellation in trace A (top left) shows that this is a 16QAM signal. The unity circle represents the DMRS occurring every seventh symbol, which are phase-modulated using an orthogonal Zadoff-Chu sequence.

Trace B (lower left) shows signal power versus frequency. The frequency scale is in 15 kHz sub-carriers numbered from -600 to 599, which represents a bandwidth of 18 MHz or 100 RB. The nominal channel bandwidth is therefore 20 MHz 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 local oscillator (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 sub-carriers 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 DMRS EVM at 0.114 percent. This is due to a +0.1 dB boost in the data power as reported in trace E, which for this example was ignored by the receiver to create data-specific EVM. Also note the DMRS 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 this impairment will be specified with a new “in-band emission” requirement as a power ratio between the allocated RB and unallocated RB. The ratio for this particular signal is around 30 dB as trace B shows. The blue dots in trace D also show the EVM of the DMRS, which is very low.

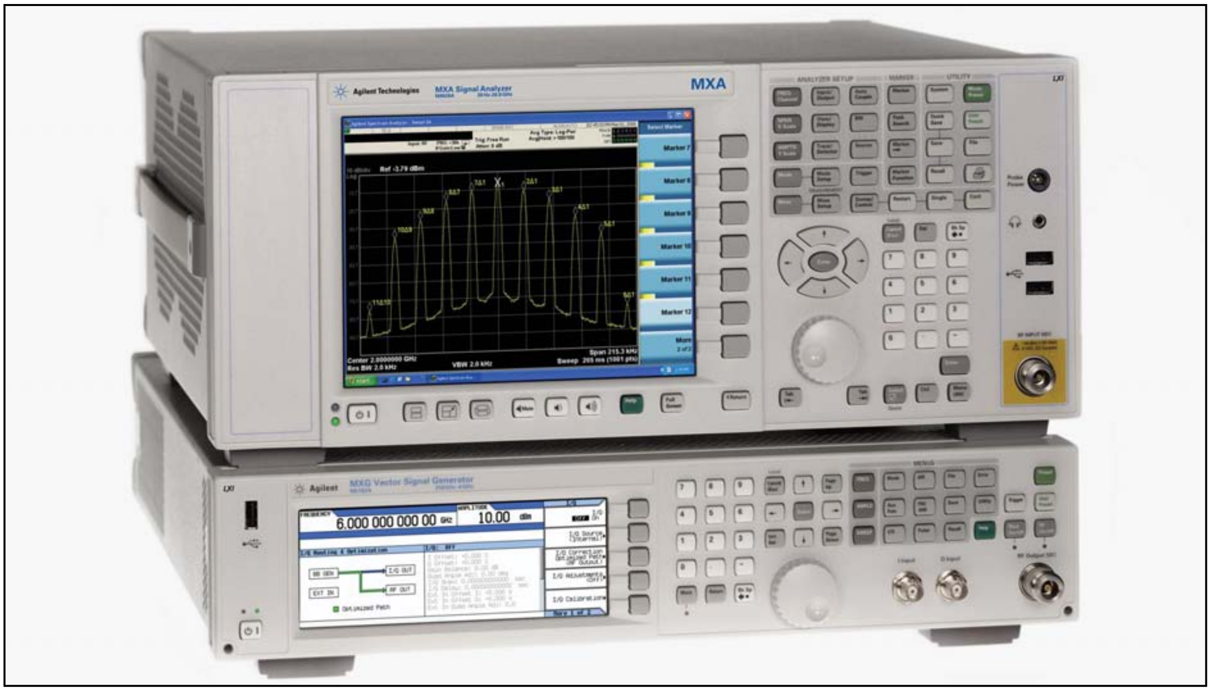

Figure 9 *Agilent's MXG Vector Signal Generator with LTE Signal Studio software and the MXA Signal Analyzer with 89600 LTE VSA software provides the most comprehensive solution for physical layer testing.*

Trace E (top right) shows a measurement of EVM by modulation type from one capture. This signal uses only the DMRS 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 blue Gaussian reference trace. As every amplifier designer knows, shaving even a tenth of a decibel shaved from the peak power budget is a significant improvement.

Agilent Design and Test Solutions to Help You Take LTE Forward

As a world leader in test and measurement solutions, Agilent Technologies is at the forefront of emerging wireless and broadband markets, such as LTE. Agilent provides the most complete suite of LTE tools, offering design and test solutions for the entire product development cycle – from RF and digital early design & test through protocol development to network deployment.

Included in this comprehensive suite of LTE tools are solutions to design and simulate LTE signals, create and measure LTE encoded signals with sources and analyzers, and test mixed analog & digital signals – see figure 9. Just added to Agilent's suite of LTE solutions is a one-box tester that provides the platform for protocol design and test solutions, in partnership with Anite. This platform will provide RF and protocol conformance test systems when they are needed. And, the newly introduced signaling analyzer enables analysis of the new LTE/SAE network.

So as you take LTE forward, Agilent will continue to clear the way.

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"3GPP: Introducing Single Carrier FDMA"
Agilent Measurement Journal, Issue 4 2008

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