Overview

Long Term Evolution (LTE) is the next step forward in cellular 3G services. Expected in the 2008 time frame, LTE is a 3GPP standard that provides for an uplink speed of up to 50 megabits per second (Mbps) and a downlink speed of up to 100 Mbps. LTE will bring many technical benefits to cellular networks. Bandwidth will be scalable from 1.25 MHz to 20 MHz. This will suit the needs of different network operators that have different bandwidth allocations, and also allow operators to provide different services based on spectrum. LTE is also expected to improve spectral efficiency in 3G networks, allowing carriers to provide more data and voice services over a given bandwidth.

This technical white paper provides an overview of the LTE physical layer (PHY), including technologies that are new to cellular such as Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) data transmission.

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1 Introduction

The 3GPP Long Term Evolution (LTE) represents a major advance in cellular technology. LTE is designed to meet carrier needs for high-speed data and media transport as well as high-capacity voice support well into the next decade. It encompasses high-speed data, multimedia unicast and multimedia broadcast services. Although technical specifications are not yet finalized, significant details are emerging. This paper focuses on the LTE physical layer (PHY).

The LTE PHY is a highly efficient means of conveying both data and control information between an enhanced base station (eNodeB) and mobile user equipment (UE). The LTE PHY employs some advanced technologies that are new to cellular applications. These include Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) data transmission. In addition, the LTE PHY uses Orthogonal Frequency Division Multiple Access (OFDMA) on the downlink (DL) and Single Carrier – Frequency Division Multiple Access (SC-FDMA) on the uplink (UL). OFDMA allows data to be directed to or from multiple users on a subcarrier-by-subcarrier basis for a specified number of symbol periods. Due to the novelty of these technologies in cellular applications, they are described separately before delving into a description of the LTE PHY.

Although the LTE specs describe both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) to separate UL and DL traffic, market preferences dictate that the majority of deployed systems will be FDD. This paper therefore describes LTE FDD systems only.

1.1 LTE Design Goals

The LTE PHY is designed to meet the following goals [1]:

1. Support scalable bandwidths of 1.25, 2.5, 5.0, 10.0 and 20.0 MHz
2. Peak data rate that scales with system bandwidth
   a. Downlink (2 Ch MIMO) peak rate of 100 Mbps in 20 MHz channel
   b. Uplink (single Ch Tx) peak rate of 50 Mbps in 20 MHz channel
3. Supported antenna configurations
   a. Downlink: 4x2, 2x2, 1x2, 1x1
   b. Uplink: 1x2, 1x1
4. Spectrum efficiency
   a. Downlink: 3 to 4 x HSDPA Rel. 6
   b. Uplink: 2 to 3 x HSUPA Rel. 6
5. Latency
   a. C-plane: <50 – 100 msec to establish U-plane
   b. U-plane: <10 msec from UE to server
6. Mobility
   A. Optimized for low speeds (<15 km/hr)
   B. High performance at speeds up to 120 km/hr
   C. Maintain link at speeds up to 350 km/hr
7. Coverage
   a. Full performance up to 5 km
   b. Slight degradation 5 km – 30 km
   c. Operation up to 100 km should not be precluded by standard

2 LTE Basic Concepts

Before jumping into a detailed description of the LTE PHY, it's worth taking a look at some of the basic technologies involved. Many methods employed in LTE are relatively new in cellular applications. These include OFDM, OFDMA, MIMO and Single Carrier Frequency Division Multiple Access (SC-FDMA). Readers familiar with these technologies can skip this material and proceed directly to Section 3.

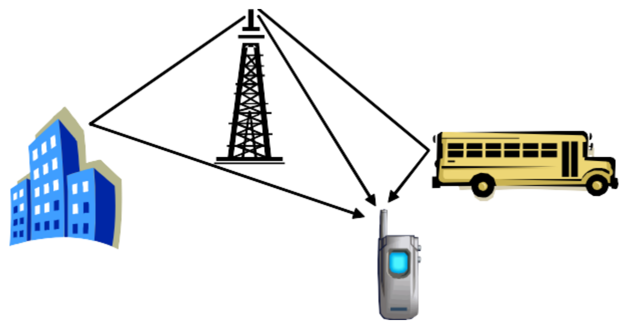
LTE employs OFDM for downlink data transmission and SC-FDMA for uplink transmission. OFDM is a well-known modulation technique, but is rather novel in cellular applications. A brief discussion of the basic properties and advantages of this method is therefore warranted.

When information is transmitted over a wireless channel, the signal can be distorted due to multipath. Typically (but not always) there is a line-of-sight path between the transmitter and receiver. In addition, there are many other paths created by signal reflection off buildings, vehicles and other obstructions as shown in Figure 2.0-1. Signals traveling along these paths all reach the receiver, but are shifted in time by an amount corresponding to the differences in the distance traveled along each path.

2.1 Single Carrier Modulation and Channel Equalization

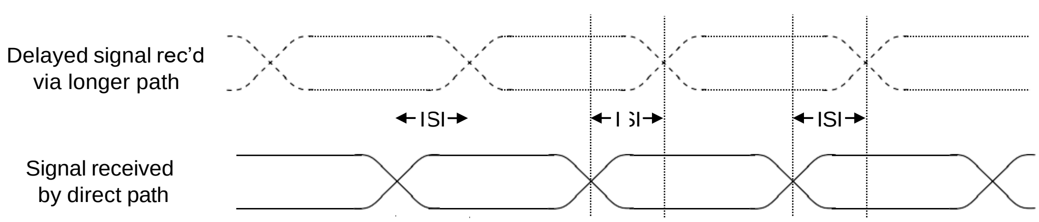
To date, cellular systems have used single carrier modulation schemes almost exclusively. Although LTE uses OFDM rather than single carrier modulation, it's instructive to briefly discuss how single carrier systems deal with multipath-induced channel distortion. This will form a point of reference from which OFDM systems can be compared and contrasted.

Figure 2.0-1 Multipath is Caused by Reflections Off Objects Such as Buildings and Vehicles



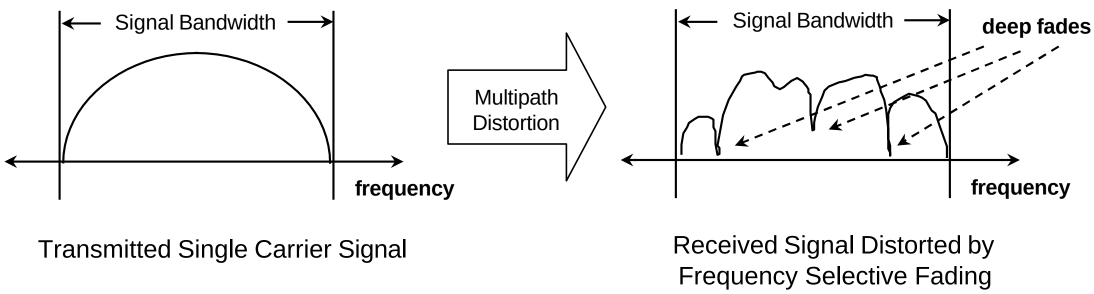
The term delay spread describes the amount of time delay at the receiver from a signal traveling from the transmitter along different paths. In cellular applications, delay spreads can be several microseconds. The delay induced by multipath can cause a symbol received along a delayed path to "bleed" into a subsequent symbol arriving at the receiver via a more direct path. This effect is depicted in Figure 2.1-1 and is referred to as inter-symbol interference (ISI). In a conventional single carrier system symbol times decrease as data rates increase. At very high data rates (with correspondingly shorter symbol periods), it is quite possible for ISI to exceed an entire symbol period and spill into a second or third subsequent symbol.

Figure 2.1-1 Multipath-Induced Time Delays Result in ISI



It's also helpful to consider the effects of multipath distortion in the frequency domain. Each different path length and reflection will result in a specific phase shift. As all of the signals are combined at the receiver, some frequencies within the signal passband undergo constructive interference (linear combination of signals in-phase), while others encounter destructive interference (linear combination of signals out-of-phase). The composite received signal is distorted by frequency selective fading (see Figure 2.1-2).

Figure 2.1-2 Longer Delay Spreads Result in Frequency Selective Fading

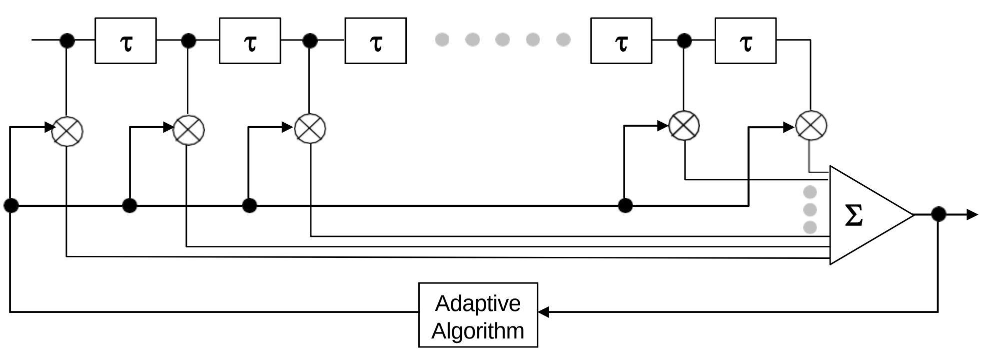


Single carrier systems compensate for channel distortion via time domain equalization. This is a substantial topic by itself, and beyond the scope of this paper. Generally, time domain equalizers compensate for multipath induced distortion by one of two methods:

1. Channel inversion: A known sequence is transmitted over the channel prior to sending information. Because the original signal is known at the receiver, a channel equalizer is able to determine the channel response and multiply the subsequent data-bearing signal by the inverse of the channel response to reverse the effects of multipath.
2. CDMA systems can employ rake equalizers to resolve the individual paths and then combine digital copies of the received signal shifted in time to enhance the receiver signal-to-noise ratio (SNR).

In either case, channel equalizer implementation becomes increasingly complex as data rates increase. Symbol times become shorter and receiver sample clocks must become correspondingly faster. ISI becomes much more severe—possibly spanning several symbol periods.

Figure 2.1-3 Transversal Filter Channel Equalizer



The finite impulse response transversal filter (see Figure 2.1-3) is a common equalizer topology. As the period of the receiver sample clock (τ) decreases, more samples are required to compensate for a given amount of delay spread. The number of delay taps increases along with the speed and complexity of the adaptive algorithm. For LTE data rates (up to 100 Mbps) and delay spreads (approaching 17 μsec), this approach to channel equalization becomes impractical. As we will discuss below, OFDM eliminates ISI in the time domain, which dramatically simplifies the task of channel compensation.

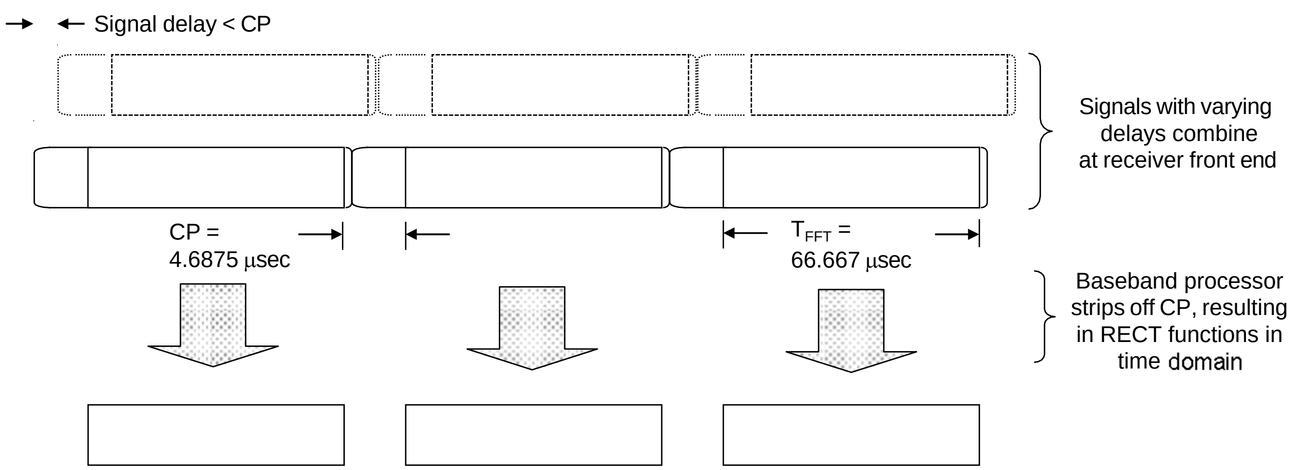
2.2 OFDM

Unlike single carrier systems described above, OFDM communication systems do not rely on increased symbol rates in order to achieve higher data rates. This makes the task of managing ISI much simpler. OFDM systems break the available bandwidth into many narrower sub-carriers and transmit the data in parallel streams. Each subcarrier is modulated using varying levels of QAM modulation, e.g. QPSK, QAM, 64QAM or possibly higher orders depending on signal quality. Each OFDM symbol is therefore a linear combination of the instantaneous signals on each of the sub-carriers in the channel. Because data is transmitted in parallel rather than serially, OFDM symbols are generally MUCH longer than symbols on single carrier systems of equivalent data rate.

There are two truly remarkable aspects of OFDM. First, each OFDM symbol is preceded by a cyclic prefix (CP), which is used to effectively eliminate ISI. Second, the sub-carriers are very tightly spaced to make efficient use of available bandwidth, yet there is virtually no interference among adjacent sub-carriers (Inter Carrier Interference, or ICI). These two unique features are actually closely related. In order to understand how OFDM deals with multipath distortion, it's useful to consider the signal in both the time and frequency domains.

To understand how OFDM deals with ISI induced by multipath, consider the time domain representation of an OFDM symbol shown in Figure 2.2-1. The OFDM symbol consists of two major components: the CP and an FFT period (TFFT). The duration of the CP is determined by the highest anticipated degree of delay spread for the targeted application. When transmitted signals arrive at the receiver by two paths of differing length, they are staggered in time as shown in Fig. 2.2-2.

Figure 2.2-2 OFDM Eliminates ISI via Longer Symbol Periods and a Cyclic Prefix



Within the CP, it is possible to have distortion from the preceding symbol. However, with a CP of sufficient duration, preceding symbols do not spill over into the FFT period; there is only interference caused by time-staggered "copies" of the current symbol. Once the channel impulse response is determined (by periodic transmission of known reference signals), distortion can be corrected by applying an amplitude and phase shift on a subcarrier-by-subcarrier basis.

Note that all of the information of relevance to the receiver is contained within the FFT period. Once the signal is received and digitized, the receiver simply throws away the CP. The result is a rectangular pulse that, within each subcarrier, is of constant amplitude over the FFT period.

The rectangular pulses resulting from decimation of the CP are central to the ability to space subcarriers very closely in frequency without creating ICI. Readers may recall that a uniform rectangular pulse (RECT function) in the time domain results in a SINC function (sin(x) / x) in the frequency domain as shown in Fig. 2.2-3. The LTE FFT Period is 67.77 µsec. Note that this is simply the inversion of the carrier spacing ($1 / \Delta f$). This results in a SINC pattern in the frequency domain with uniformly spaced zero-crossings at 15 kHz intervals—precisely at the center of the adjacent subcarrier. It is therefore possible to sample at the center frequency of each subcarrier while encountering no interference from neighboring subcarriers (zero-ICI).