Comprehending the technology behind the UMTS wideband CDMA physical layer

The technology used in the UMTS physical layer is based on direct sequence spread spectrum. Gaining a fundamental concept of how the pieces come together enable the engineer to capitalize on the benefits of the technology.

By Louis Litwin

The physical layer of the universal mobile telecommunications system (UMTS) wideband code-division multiple access (WCDMA) standard uses direct sequence spread spectrum (DSSS) modulation with a chip rate of 3.84 Mcps. The channel bandwidth is 5 MHz and this wider bandwidth (compared to 2G systems such as IS-95, which have a bandwidth of 1.25 MHz) has benefits such as higher data rates and improved multipath resolution.

For example, WCDMA has a multipath resolution of approximately 78 m (meters) versus IS-95's resolution of approximately 244 m.

Error control coding options include rate 1/2 and 1/3 convolutional coding as well as rate 1/3 turbo coding. The data rates supported range from a few kb/s to 2 Mb/s. The physical layer supports two modes of operation: FDD and TDD.

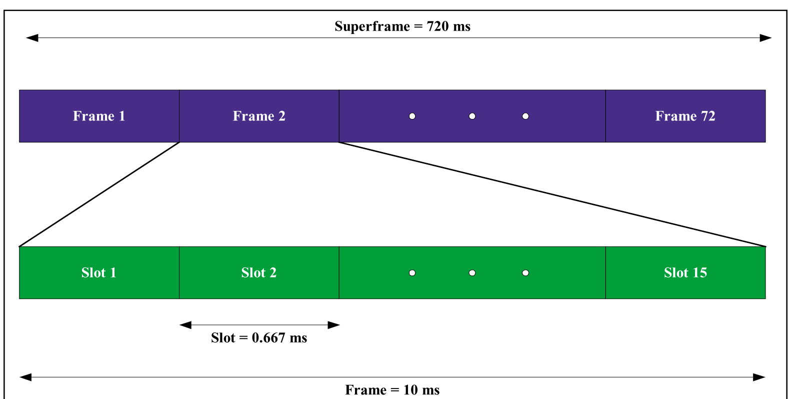

Figure 1: Basic structure of a WCDMA physical layer radio frame.

FDD and TDD operational modes

The frequency-division duplex (FDD) mode carries the uplink and downlink channels on separate frequency bands of 5 MHz each. This mode is typically used for large outdoor cells because it can support a larger number of users than TDD mode. In time-division duplex (TDD) mode, the transmissions share the same frequency band by sending the uplink and downlink channels during different time slots. The TDD mode does not support as many users as the FDD mode, and hence, TDD mode is more suitable for smaller cells. TDD mode also is more suited for carrying asymmetric traffic compared to FDD mode.

The uplink and downlink transmissions in FDD mode are assigned fixed and equal frequency bands. This assignment works well when carrying voice traffic since such traffic tends to have uplink and downlink transmissions of approximately equal size. However, TDD mode is more efficient for carrying asymmetric traffic, such as Internet data.

Internet data tends to have downlink transmissions that are much larger than the uplink transmissions.

For example, a user's HTTP request for a Web page requires a brief uplink transmission, whereas downloading the Web page might require a large downlink transmission to carry text, audio and video. TDD mode is more suited to this asymmetric type of transmission because the ratio of the uplink and downlink bandwidths can be modified by assigning more or fewer time slots to each link.

Thus FDD mode, with its fixed uplink/downlink allocation and larger capacity, is typically used in large outdoor cells that primarily carry voice traffic.

On the other hand, TDD mode is typically used for indoor cells since such cells tend to be smaller and have a higher tendency to carry asymmetric data traffic. Because of the popularity of FDD mode, the remainder of this article will only focus on the WCDMA FDD mode.

Radio frame format

The basic transmission element in the FDD physical layer is a radio frame. A radio frame has a duration of 10 ms, and it is broken down into 15 time slots of 0.667 ms each. Each time slot contains 2,560 chips and thus the entire 10 ms radio frame contains 38,400 chips.

The purpose of the time slot structure is to provide a timing framework for determining when various events can occur. For example, a user's data rate can change for every frame, and power control commands are sent every slot (thus giving WCDMA a power control rate of 1,500 Hz). The data in WCDMA is modified by both spreading and scrambling codes prior to transmission.

The next sections will discuss these codes.

Spreading codes

Spreading codes are an integral part of the DSSS modulation process. The codes are used to spread the spectrum of the transmitted signal by multiply-

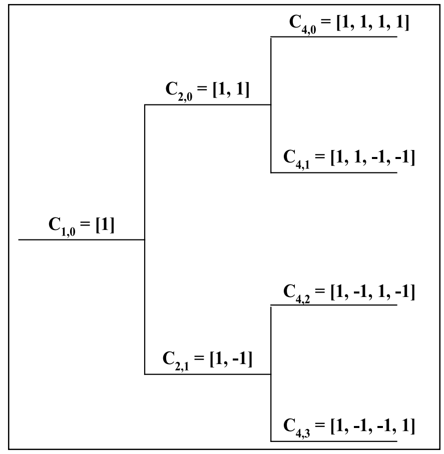

Figure 2: First few levels of the OVSF code tree.

ing the data bits by the higher frequency spreading code, thus increasing the data rate of the signal.

The spreading codes used in WCDMA are called orthogonal variable spreading factor (OVSF) codes, and the spreading factor can vary from SF = 4 to SF = 512. These codes are formed from a code tree where all codes at a given spreading factor are orthogonal to each other. The use of OVSF codes allows various codes of different lengths to be orthogonal to each other.

Since the 3.84 Mcps chip rate is held constant, higher data rates are obtained by using shorter spreading codes and lower data rates are obtained using longer spreading codes. The number of available codes of a given length is equal to the spreading factor.

For example, there are 512 spreading codes at a spreading factor of SF = 512. Decreasing the spreading factor increases the data rate but reduces the number of users that can be supported because fewer codes are available at the shorter spreading factors. Shorter spreading codes also result in a lower correlation gain at the receiver and thus the transmit power must be increased in order to maintain the same energy per bit across all spreading factors.

Scrambling Codes

Scrambling codes are pseudorandom sequences that also are multiplied by the data.

However, unlike spreading codes, the scrambling codes do not change the data rate of the signal. Instead, the codes are overlaid on top of the spread data as a mask to identify the source of the data. The typical long scrambling

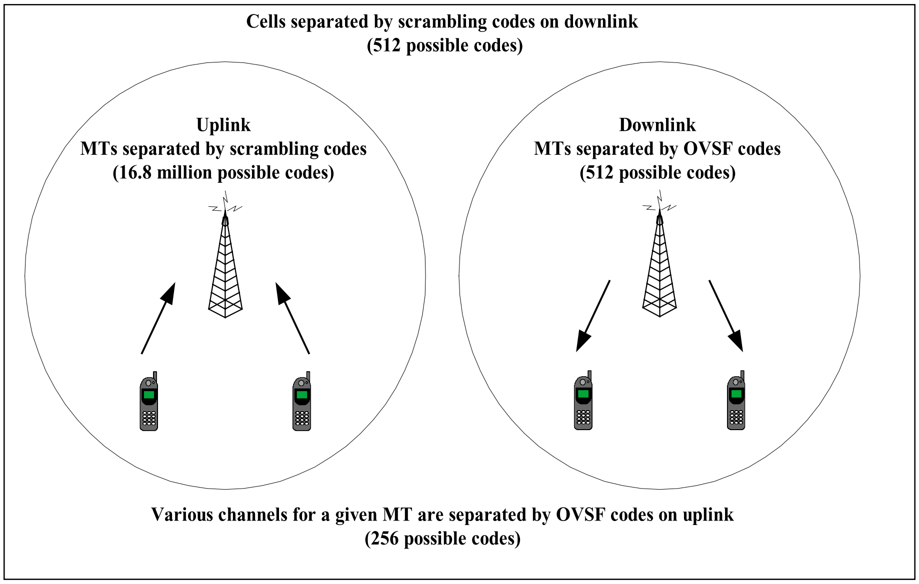

Figure 3: Summary of code usage in uplink and downlink transmissions.

codes are formed by truncating Gold codes to a length of 38,400 chips (e.g., a frame length). These codes are used when the base station has implemented a rake receiver.

In addition, short scrambling codes can be used when the base station has implemented multiuser detection (MUD) algorithms. The shorter scrambling code length simplifies the implementation of these MUD algorithms.

Code usage

These spreading and scrambling codes are used in different ways depending on whether the transmission is on the uplink or downlink. On the uplink, the signals from different cellular phones, or mobile terminals (MTs), are separated by overlaying the signal with different scrambling codes. On the uplink, there are a total of 16.8 million possible scrambling codes that can be used. The base station (BS) assigns these codes to each MT in its cell. A given MT will simultaneously transmit several different physical channels on the uplink, and these channels are separated by using different codes from the OVSF code tree. The range of spreading factors on the uplink goes from SF = 4 to SF = 256. The same OVSF code tree is used by all MTs, and thus, it is possible that multiple MTs will be transmitting using the same spreading code. However, it is the different overlaid scrambling codes used by the MTs that allow the BS to differentiate the signals from the MTs in its cell.

On the downlink side, the base stations separate themselves by transmitting with different scrambling codes. Thus all the downlink signals in a given cell will be overlaid with the same scrambling code. Unlike the uplink, the number of possible scrambling codes is only 512. This number is intentionally kept small because doing so reduces the complexity of the cell search procedure performed by the MTs.

The downlink physical channels sent to the MTs in the cell are separated by transmitting the channels for different MTs using spreading codes taken from a single code tree. The range of spreading factors for the downlink goes from SF = 4 to SF = 512. Because the spreading codes for all MTs in a given cell are taken from the same code tree, trade-offs must be made when assigning codes to various MTs. If a high data rate code with a short spreading factor is assigned to an MT, this assignment prevents all of the codes further down that branch in the code tree from being used (because codes from a given branch are not orthogonal to one another). Therefore, although a large number of users can be supported in a given cell at low data rates, only a few users can be supported at high data rates.

Uplink dedicated physical channels

There are two types of physical channels — dedicated and common. A dedicated channel is assigned to and used by only one user. A common channel is shared by several (possibly all) users in a cell. On the uplink there are two dedicated physical channels.

The dedicated physical data channel (DPDCH) and the dedicated physical control channel (DPCCH) are I/Q multiplexed (i.e., one is transmitted on the real channel and one on the imaginary channel) on the uplink. The DPDCH carries data dedicated for one user. For example, this channel would be used to carry voice traffic as well as audio/video data from a specific user.

Typically there is only one DPDCH, however it is possible to transmit six simultaneous DPDCHs when the spreading factor is SF = 4. The six DPDCHs are carried on three spreading codes by transmitting three DPDCHs on the real channel and three DPDCHs on the imaginary channel.

The DPCCH is used to carry physical layer control information associated with the DPDCH. Pilot bits are carried on the DPCCH in order to aid the base station with channel estimation and carrier recovery for the DPDCH. The DPCCH also carries power control commands, feedback information as well as information about the format of the data being carried over the DPDCH. Regardless of the number of DPDCH channels, there is always only one DPCCH.

Uplink channel topology

The physical random access channel (PRACH) is used to carry random access transmissions. For example, random access transmissions are used when the MT wishes to set up a connection with the base station in order to place an outgoing call. The random access procedure is based on the slotted ALOHA protocol and it uses open-loop power control.

The open-loop power control works as follows. First, the MT transmits a PRACH preamble to the base station. If the BS does not acknowledge the preamble, the MT transmits the preamble again but at a higher power. This process continues until the received signal strength at the BS is strong enough for reception. At this point, the BS sends an acknowledgement to the MT.

Following this acknowledgement, the MT sends the PRACH message at the same power level as the last preamble transmission. Since this power level is only valid for a very short period, the PRACH message part can only be one or two frames in duration. The PRACH message part consists of both a data and control channel.

The physical common packet channel (PCPCH) is a shared channel that carries packet-based data transmissions. The channel access is based on the carrier sense multiple access with collision detection (CSMA/CD) protocol where the MT first senses the medium to see if it is free before transmitting. If it detects a collision, the MT backs off for a random amount of time before re-trying the transmission.

Downlink channel topology

The dedicated physical channel (DPCH) is the downlink equivalent of the DPDCH and DPCCH channels. It is a single channel that carries both dedicated data information as well as control information. It can be viewed as a time-multiplexed version of the DPDCH and DPCCH channels.

The common pilot channel (CPICH)

is a continuous downlink pilot signal that contains a known training sequence scrambled by the current cell's scrambling code. This channel is used by the MT as a reference signal for a variety of signal processing operations, such as carrier synchronization and channel estimation.

The common control physical channel (CCPCH) is used to carry several upper-layer transport channels. The CCPCH carries the broadcast transport channel that is used to send network and cell-specific information to all MTs in a cell. The CCPCH also carries the forward access transport channel which sends information to an MT after the MT makes a random access attempt on the PRACH uplink physical channel.

The paging channel is also carried on the CCPCH. The paging channel carries pages from the base station to an MT to notify the MT that the base station has information for the MT. For example, the base station will use the paging channel to page the MT in order to notify it of an incoming call.

The synchronization channel (SCH) is the first channel that an MT looks for at start-up. The SCH is a sparse channel that is only active during the first 256 chips of each slot. The SCH is made up of two subchannels, primary and secondary. The primary SCH carries the same signal for all cells in the system and it is used by the MT to obtain chip, symbol and slot synchronization. The secondary SCH is different for each cell. The secondary SCH channel carries a pattern of secondary synchronization codes (SSCs) that repeat every frame. Once the MT receives this sequence, it will have frame synchronization.

In addition, the pattern will identify which scrambling code group the current cell's scrambling code belongs to. There are 64 scrambling code groups, and each group contains eight scrambling codes. Once the MT has determined the current cell's scrambling code group, the search for the current cell's scrambling code will be narrowed to the eight codes in that group.

The physical downlink shared channel (PDSCH) is used to carry the downlink shared transport channel. This channel carries control information for several users that share the channel.

Indicator channels

There are also other types of channels, known as indicator channels.

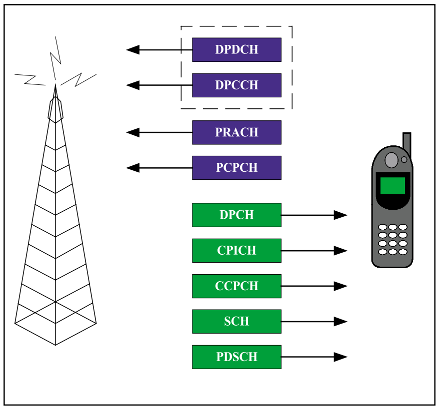

Figure 4: Summary of uplink/downlink physical channels.

There are several of these channels, and they are used to carry specific indicator messages. For example, there is a paging indicator channel (PICH) that carries paging indicators. This channel is used to notify all MTs in a given paging group that there is a page from the base station for an MT in that paging group.

Another indicator channel is the acquisition indicator channel (AICH). The AICH is used by the base station to notify the MT that it has received the MT's PRACH preamble during the open-loop power control phase of a random access transmission.

Mobile terminal Rx processing

After power-up, the mobile terminal has to perform several operations before voice/data communications can begin. First, the receiver needs to implement automatic gain control (AGC) in order to scale the received signal power and prevent clipping at the analog-to-digital (A/D) converter. This process first can be performed on the SCH channel, and later the descrambled CPICH pilot can be used once the cell's scrambling code is acquired.

Next, the receiver needs to acquire timing synchronization. Timing synchronization can be achieved from the SCH channel. The MT will search for the strongest SCH signal that it can find, and that signal determines which cell the MT will initially communicate with. Since the SCH channel is periodic, the receiver can correlate against the primary SCH to derive a timing error. Based on this channel, the receiver can achieve chip, symbol and slot synchronization.

However, since the primary SCH channel transmits the same sequence in all slots, the receiver cannot yet determine the location of frame boundaries. Once the secondary SCH channel is acquired, the receiver will have frame synchronization because the channel carries a pattern that repeats every frame.

Based on this secondary SCH pattern, the MT will know which scrambling code group the current cell's scrambling code belongs to. There are 512 scrambling code groups and the Secondary SCH indicates which group the current cell's code is in. Since there are only eight scrambling codes in a group, the MT can determine which scrambling code is being used by correlating against the CPICH pilot channel using each of the eight scrambling codes in the cell's code group. The current cell's code is identified by looking for the largest correlation peak out of all eight correlations.

After the cell's scrambling code has been determined, all downlink channels can be descrambled and acquired. The MT will first use the CPICH pilot channel to derive an error for carrier frequency synchronization. This step removes any residual frequency errors that result from a frequency offset between the oscillators at the base station and the MT.

Next, the MT uses the CPICH pilot channel to generate an estimate of the multipath channel that the downlink signal has travelled through. This channel estimate is used by the rake receiver to determine which channel paths to assign rake fingers to.

Getting signal strength up

The rake receiver is used to constructively combine energy from various channel paths in order to allow the receiver to work with a stronger signal. Thus, instead of suppressing the energy from other multipaths, the rake receiver actually combines this energy.

The rake fingers are each assigned to a given channel path, and they correlate against the signal corresponding to that channel delay. The channel estimate value for that path is used to weight the signal prior to combining the signals from multiple paths. This weighting is an important step, because it aligns the phases of all of the signals so that they can be constructively combined. Without this step, it is possible that the phases of the various signals could be such that the signals could be destructively combined, and in such a case, the signal power of the resulting signal would be lessened.

The rake receiver is used to first acquire the broadcast transport channel that is carried on the CCPCH physical channel. This channel will inform the receiver of which random access codes are available in the cell. The MT will use one of the available codes to begin a random access procedure on the PRACH channel. Once it has contacted the base station, the MT will register itself with the base station so that the network knows the location and capabilities of the MT. The base station also will assign the MT to a paging group.

The MT will then go into sleep mode where most of the receiver is shut down to conserve battery power. The MT will wake up if the user wishes to make a call.

In addition, the MT will periodically wake up to monitor the paging indicator channel. If this channel indicates that there is a page for the MT's assigned paging group, the MT will decode the paging channel to see if the page is actually for the MT. The base station uses pages to contact the MT when there is data for the MT. An example would be an incoming phone call for the MT. The receiver would then acquire the DPDCH and DPCCH channels to receive the data.

Conclusions

This article provided a basic overview of some of the main features of the WCDMA physical layer standard. In addition, some insight was given into the signal processing that must be performed by the receiver after power-up. The interested reader can learn more about the various details of the standard from the references listed below.

RF

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