RF Lecture Series
Modulation Fundamentals
Introduction to WCDMA

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1. Introduction

Second generation (2G) mobile communication standards were developed to provide higher bandwidth efficiency, security and digital modulation schemes. Third generation (3G) wireless capability has been developed in response to a growing demand in data services. The International Telecommunications Union (ITU) defined the specification known as the International Mobile Telecommunications 2000 (IMT-2000) with the goal of developing a global standard that enables worldwide roaming, multimedia application services, improved spectral efficiency, and flexibility of evolution from existing standards. The evolution goal simplified the transition of carriers from 2/2.5G CDMA based networks to WCDMA. The targeted data rates were 2Mbps for fixed, 384kbps for pedestrians and 144kbps for vehicular access.

Different regional solutions were proposed as solutions to the requirements of IMT-2000. These included Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) utilizing Frequency Division Duplex (FDD) and Time Division Duplex (TDD). The fragmentation of the proposals led to the creation of two working groups. One, known as the Third Generation Partnership Project (3GPP) is working on the Unified Mobile Telecommunication Standard (UMTS) based on WCDMA. The other, 3GPP2 works on CDMA2000.

A transition from 2G can be modeled with the following table (

Table 1 - Standards Differentiation) which demonstrates the key differentiating capabilities of each generation and other IMT-2000 implementations of 3G.

Table 1 - Standards Differentiation [1]

Generation	Technology	Data Rate	Bandwidth	Data Network
2G	GSM	9.6 or 14.4 kbps	200 kHz	Circuit Switched
2G	CDMA (IS-95)	9.6 or 14.4 kbps	1.25 MHz	Circuit Switched
2.5G	GPRS	128 kbps	200 kHz	Circuit/Packet
2.5G	Edge	384 kbps	200 kHz	Circuit/Packet
2.5G	CDMA2000-1XRTT	153 kbps	1.25 MHz	Circuit/Packet
3G	**WCDMA (UMTS 99)**	**384 kbps**	**5 MHz**	**Packet**

3G	**WCDMA (HSPA)**	**144 kbps, 384 kbps (5.76/14.4 Mbps)**	**5 MHz**	**Packet**
3G	CDMA2000-DO/EV	144 kbps, 384 kbps, 2Mbps	1.25 MHz	Packet
3G	TD-CDMA	144 kbps, 384 kbps, 2Mbps	5 MHz	Packet
3G	TD-SCDMA	144 kbps, 384 kbps, 2Mbps	1.6 MHz	Packet

2. WCDMA - 3GPP Release 5 (HSDPA) and Release 6 (HSUPA)

The 3GPP 1999 standard was focused on data transmission flexibility while maintaining compatibility with previous generation resources. As such, the initial data rate was somewhat limited relative to the goals outlined by IMT-2000. With the later standards the throughput was greatly enhanced. With 3GPP Release 5 the standard incorporated High Speed Downlink Packet Access (HSDPA). The features of HSDPA provided adaptive modulation and coding, shared channel transmission and a shorter transmission time interval. To achieve the improvement in data rates it was necessary to enhance the modulation scheme to incorporate 16QAM in addition to the existing QPSK. This allows HSDPA to achieve a 14.4 Mbit theoretical throughput utilizing 16QAM modulation.

3GPP Release 6 focused on the improvement of the uplink channel through the implementation of High Speed Uplink Packet Access (HSUPA). HSUPA provides uplink data rates as high as 5.76 Mbps.

The key specifications are detailed in the following tables:

Table 2 - WCDMA Specifications

Channel Bandwidth	5 MHz
Duplex Mode	FDD and TDD
Downlink RF channel Structure	Direct Spread
Chip Rate	3.84 Mcps
Frame Length	10 ms
Spreading Modulation	Balanced QPSK (downlink) Dual-Channel QPSK (uplink) Complex spreading circuit
Data Modulation	Downlink – QPSK, 16QAM and 64QAM Uplink – OCQPSK, BPSK and 4PAM
Channel Coding	Convolutional and turbo codes
Channel multiplexing in downlink	Data and control channels time multiplexed
Channel multiplexing in uplink	Control and pilot channel time multiplexed I&Q multiplexing for data and control channel
Multirate	Variable spreading and multicode
Spreading factors	4-256 chips (uplink), 4-512 chips (downlink)
Power control	Open and fast closed loop (1.6 KHz)

Spreading (downlink)	Orthogonal Variable Spreading Factor (OVSF) Sequences for channel separation
Spreading (uplink)	OVSF Sequences

Table 3 - UMTS-FDD Frequency Bands [2]

Operating Band	Frequency Band	Common Name	UL Frequencies UE transmit (MHz)	DL Frequencies UE receive (MHz)	Region
I	2100	IMT	1920 - 1980	2110 - 2170	Europe, Asia, Japan
II	1900	PCS	1850 - 1910	1930 - 1990	North America
III	1800	DCS	1710 - 1785	1805 - 1880	Europe, Asia
IV	1700	AWS	1710 - 1755	2110 - 2155	USA, Canada
V	850	CLR	824 - 849	869 - 894	North America, Australia
VI	800		830 - 840	875 - 885	Japan
VIII	900	GSM	880 - 915	925 - 960	Europe, Asia
IX	1800		1749.9 - 1784.9	1844.9 - 1879.9	Japan

3. WCDMA Modulation Fundamentals

WCDMA provides the ability to dynamically assign data rates and modulation format to match the individual user demand.

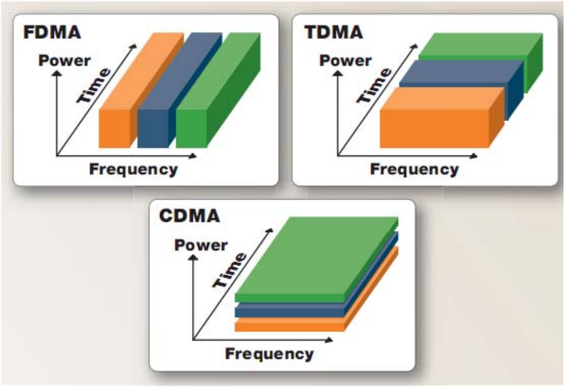

Figure 1 - Multiple Access Systems

WCDMA differs from other multiple access schemes (Figure 1 - Multiple Access Systems) in the manner in which it segments concurrent individual users. Early analog cellular utilized Frequency Division Multiple Access (FDMA). FDMA splits available frequency spectrum among users over time. Time Division Multiple Access (TDMA), which is used in the GSM standard, allocates the bandwidth to an individual user but switches user's access over time. As in Code Division Multiple Access (CDMA), WCDMA is principally based on the principal of spread spectrum. The bandwidth is shared among multiple users concurrently. User's signals are differentiated through Direct Sequence Spread Spectrum (DS-SS) which utilizes a discrete code per user to differentiate the user's channel.

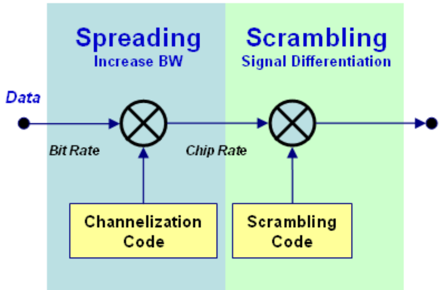

Figure 2 - Spreading and Scrambling

The bandwidth necessary to represent a signal is directly related to the data rate and available dynamic range. To increase resistance to interference the signal can be translated to utilize a broader frequency which is called spectrum spreading. In this case the original signal is multiplied with a high bandwidth signal known as a channelization code (OVSF). This high bandwidth signal can be pseudo-random and look like noise, but is reproducible. This high bandwidth signal is reused on the receiving end to recover the original signal. The high bandwidth signal is referred to as a spreading or channelization 'code' symbol called 'chips' [3]. The application of a discrete scrambling code (Figure 2 - Spreading and Scrambling) allows the differentiation of the individual user's channel within the common bandwidth.

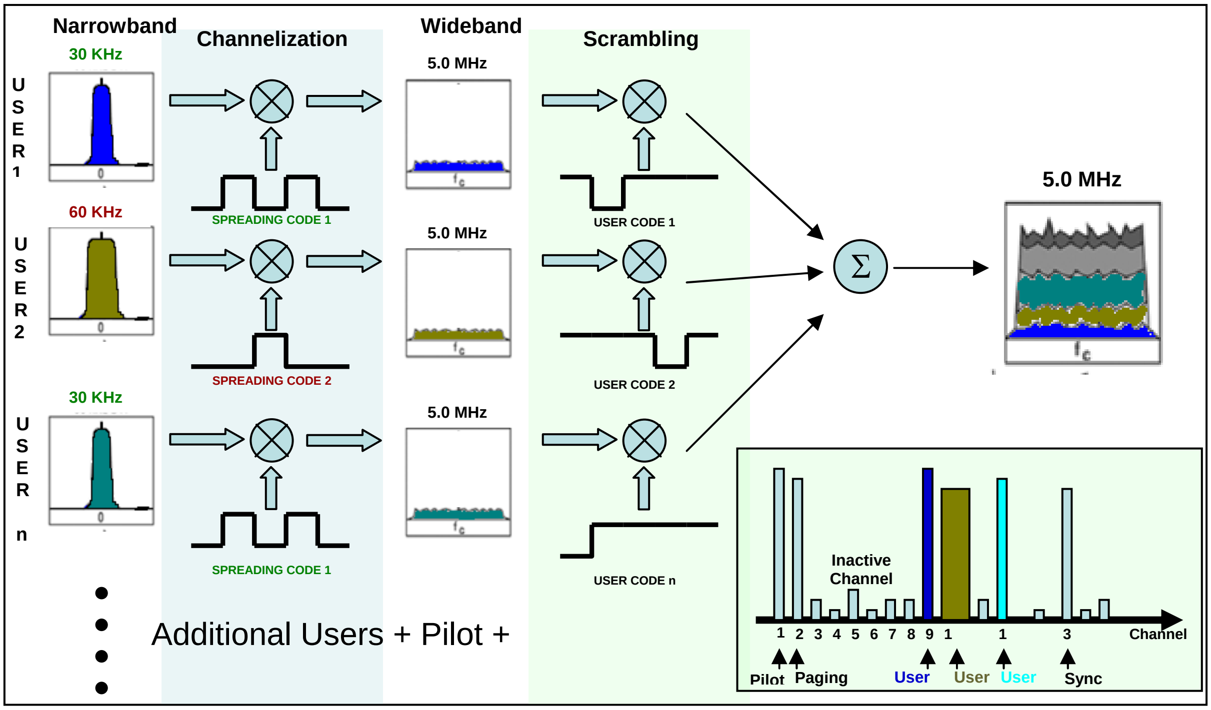

Figure 3 – WCDMA – Simplified Model of Coding and Multiple Access

For a more descriptive example as in

Figure 3 – WCDMA – Simplified Model of Coding and Multiple Access, 30 KHz represents the bandwidth for a single user voice transmission. The encoding and spreading (channelization), based on code, develops a single user data representation (spread) which occupies 5.0 MHz. This spread for a single user coded data is called a chip. The spread rate is related in terms of Mega-chips-per-second (Mcps) which is 3.84 Mcps for W-CDMA.

The spreading varies to support the variable data rates. The spreading factor determines the ratio of pre-spreading bandwidth to the final channel bandwidth. The uplink data rate can vary up to approximately 2 Mbps to support data transmission as shown in Table 4 - Dedicated Physical Data Channel (DPDCH) Data Rate.

Table 4 - Dedicated Physical Data Channel (DPDCH) Data Rate

DPDCH Uplink/Downlink Spreading Factor	Downlink Channel Bit Rate (kbps)	Uplink Channel Bit Rate (kbps)
512	15	N/A
256	30	15
128	60	30
64	120	60
32	240	120
16	480	240
8	960	480
4	1920	960

Note that the spreading factor utilized is based on a theoretically unlimited available Signal to Noise Ratio (SNR). The actual SNR of the frequency band utilized combined with the number of users competing to utilize this bandwidth determines the spreading factor chosen for a specific channel. This ability to vary rates per user over time to compensate for dynamically changing requirements and environments is a key component benefit of WCDMA.

WCDMA uplink (UL) and downlink (DL) channels are segmented into time slots and frames (Figure 4 - Slot and Frame Structure). A slot is 666.6667 uSeconds in length and is equal to 2560 chips of the system chip rate (3.84Mcps). A sum of 15 slots composes a single frame.

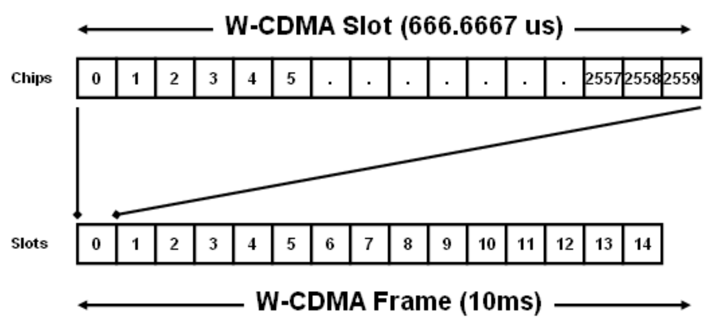

Figure 4 - Slot and Frame Structure

3.1 WCDMA Protocol

The protocol of WCDMA includes the Physical Layer, Data Link Layer, and Network Layer as Layers 1, 2 and 3, respectively as shown in Figure 5 - WCDMA Protocol. Understanding the channel components is necessary to understand the construct of the signals utilized to test the operational performance of the device under test. The data link layer includes radio link control (RLC) which is responsible for the transfer of user data, error correction, flow control, protocol error detection and recovery and ciphering. The data link layer also includes the MAC functionality which is responsible for multiplexing/de-multiplexing of logic channels onto a common transport channel. The physical layer maps the transport to physical channels and includes the RF functions. These include frequency synchronization, time synchronization, rate-matching, spreading and modulation, power control and handoff.

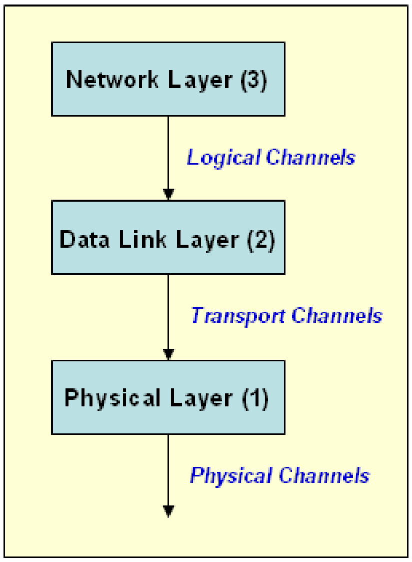

Figure 5 - WCDMA Protocol

Logical channels are the information content, which will ultimately be transmitted over the physical channels. Logical channels include the Broadcast Control Channel (BCCH), the Paging Control Channel (PCCH), the Common Control Channel (CCCH), and Dedicated Control and Traffic Channels (DCCH, DTCH). The transport channels support sharing physical resources between multiple services. Therefore each service, such as data, voice, or signaling can have different data rates.

3.1.1 Transport Channels

The transport channels are then multiplexed via one or more physical channels. High data rate services or a combination of lower rate transport channels may be multiplexed into several physical channels.

Table 5 - Transport Channels

Transport Channel	**Description**
DCH	***Dedicated CHannel* is a dedicated transport channel that carries user data and is specific to a single user. In a voice conversation the coded voice uses the DCH.**
RACH	Random Access Channel which is primarily used to signal initial system access in the uplink when a user wants to gain access to the network.
BCH	*Broadcast CHannel* is used in the downlink to transmit system

	information over the entire coverage area of a cell.
PCH	*Paging CHannel* is in the downlink to page a specific UE.
FACH	*Forward Access CHannel* is used to send downlink control information to one or more users in a cell.
DSCH	***Downlink Shared CHannel* is used to transmit dedicated user data or control signals to one or more users.**
CPCH	*Common Packet CHannel* is similar to the RACH but can last several frames. Therefore it can transmit more data in a single burst to all users in a cell.

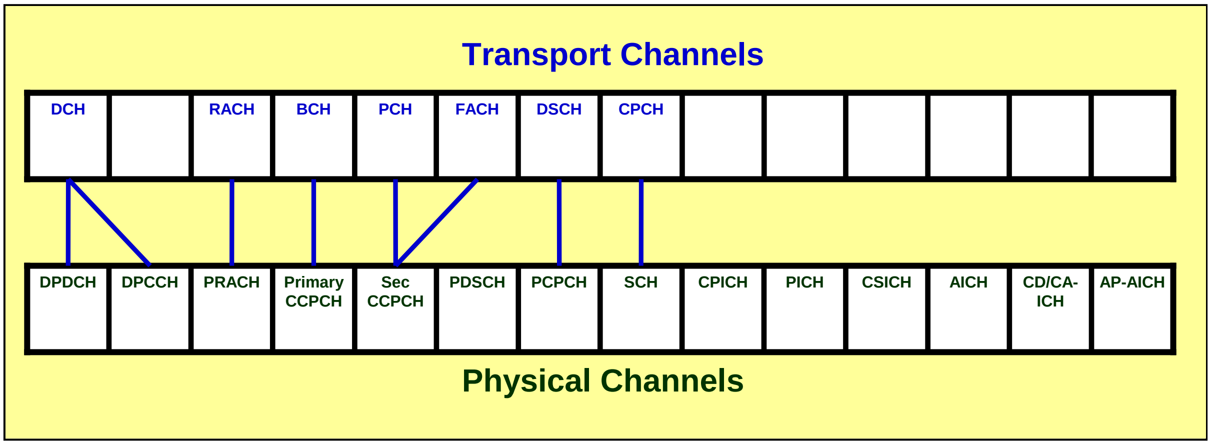

Figure 6 - Channel Mapping

3.1.2. Physical Channels

Physical Channel	Description
DPDCH	*Dedicated Physical Data CHannel* carries data from the DCH transport channel.
DPCCH	*Dedicated Physical Control CHannel* carries control information from the DCH transport channel.
PRACH	*Physical Random Access CHannel* is used in the **uplink** to carry the RACH transport channels.
(P/S)-CCPCH	Primary *Common Control Physical CHannel* is used on the **downlink** to carry the BCH transport channel. The Secondary CCPCH is used on the downlink to carry the FACH and PCH.
PDSCH	*Physical* ***Downlink*** *Shared CHannel* is used in the downlink to carry the DSCH transport channel.
PCPCH	*Physical Common Packet CHannel* is used in the **uplink** to carry the uplink CPCH transport channel.
(P/S)-SCH	*Synchronization CHannel* is transmitted by the base station and includes the Primary Synchronization Code (PSC) which is a 256-chip code word that is identical in every cell and a secondary PCS to identify the primary scrambling code group of the cell.
CPICH	*Common Pilot CHannel* is always transmitted by the base station and is

	continuous loop broadcast of the Base Transceiver Station (BTS) scrambling code. It is time multiplexed with the SCH.
PICH, CSICH, AICH, CD/CA-ICH, AP-AICH	Indicator channels for synchronization.

Although the mapping of the physical channels can be very complex, a brief overview of the key components necessary to support Downlink and Uplink testing are detailed in the following sections.

The SCH is transmitted during the first 256 chips of each time slot while the P-CCPCH is off. During the remaining 2304 chips of each slot the P-CCPCH is transmitted, which contains 18 bits of broadcast data (Broadcast Transport Channel (BCH) information) at a rate of 15 kbps. Since the cell's broadcast parameters message will require more than 18 bits, the broadcast information may span several frames.

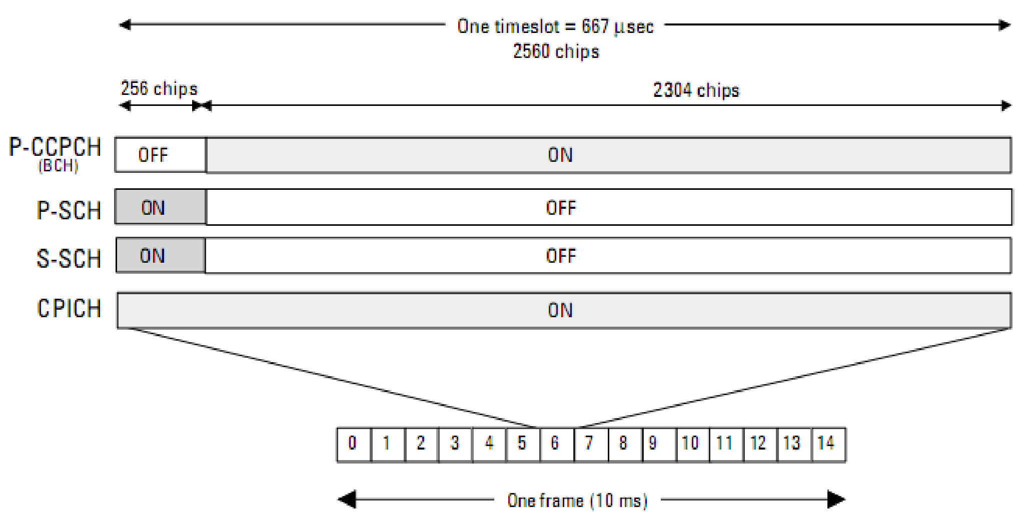

Figure 7 - Downlink Physical Channel Mapping.

The Dedicated Physical Channel (DPCH) carries all the user data and user signaling, as well as physical channel control bits for the slot format and the UE inner loop power control. The DPCH consists of the DPDCH and the DPCCH. *The user's digitized voice and/or digital data, along with layer 3 signaling data, are carried on the DPDCH.* The user data and signaling data are individually treated with error protection coding and interleaving, then multiplexed together to form the DPDCH. The DPDCH is then multiplexed with the DPCCH, which contains the Transmit Power Control (TPC) bits (to control the UE transmit power), Transport Format Combination indicator (TFCI) bits (indicates the slot format and data rate), and embedded Pilot bits (short synchronization patterns embedded within each slot).

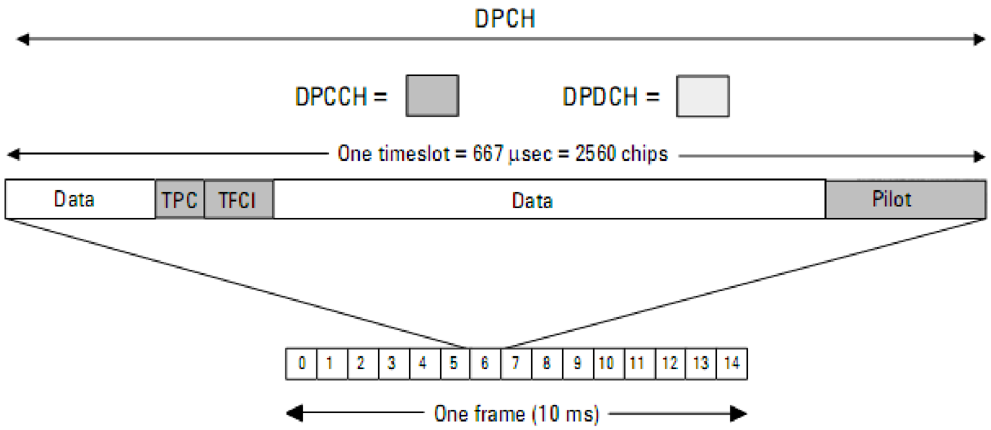

Figure 8 - DPCH Mapping

The Uplink consists of a Physical Random Access Channel (PRACH), a Physical Common Packet Channel (PCPCH), and Dedicated Physical Data and Control Channels (DPDCH/DPCCH).

The PRACH carries the RACH transport channel, which is used by the UE to request connection to the network as well as for intermittent services such as low duty cycle packet data. PRACH transmissions begin with a short preamble pattern that alerts the BTS of the forthcoming PRACH access message. The preamble consists of a complex signature and a scrambling code. The signature is a series of 16 bits that is repeated 256 times within a single preamble. All BTS use the same 16 signatures. The BTS tells each UE which signature to use and then uses the signature to determine which UE it is communicating with. The scrambling code is used by the BTS to determine that the PRACH transmission is intended for that BTS.

The message part is transmitted as part of the PRACH after the UE receives acknowledgment from the BTS on the DL AICH. It consists of two parts: a control part and a data part. These two parts are transmitted in parallel. The control part carries the pilot and TFCI bits. The data part consists only of data bits that contain the information the UE wants to send to the network. The message part uses the same scrambling code used in the preamble.

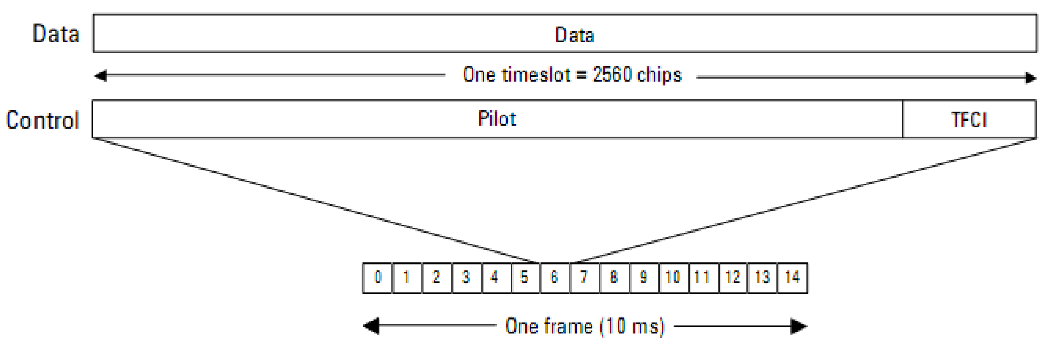

Figure 9 - PRACH Slot

The PCPCH carries the CPCH transport channel and it is used for UL packet data transmission.

The UL DPDCH/DPCCH carries the user's digitized voice and data channels along with layer 3 signaling data. The payload data and signaling data (DPDCH) are transmitted on the "I" path of the QPSK modulator; the power control, pilot, and other overhead bits (DPCCH) are transmitted on the "Q" path. Figure 10 - Uplink DPDCH and DPCCH Slot shows the slot structure. Each channel is spread by an OVSF code and its amplitude can be individually adjusted. Before modulation, the composite spread signal is scrambled with a special function that minimizes the signal transitions across the origin of the IQ plane and the 0° phase shift transitions. This improves the peak-to-average power ratio of the signal [8].

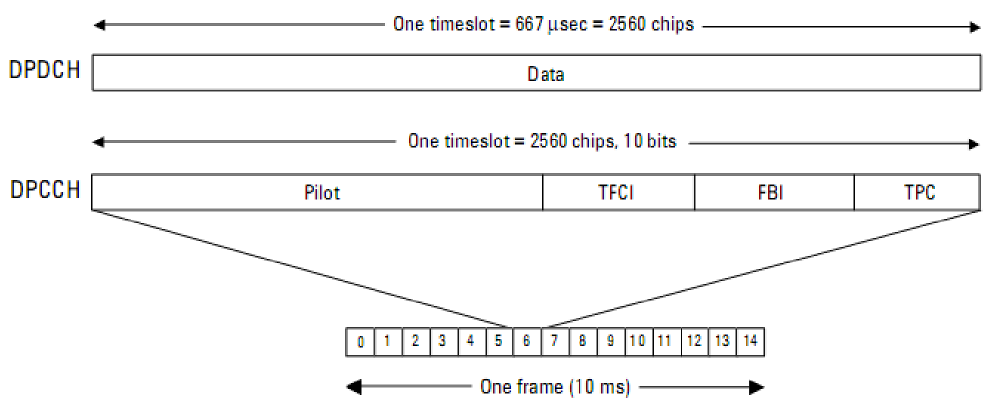

Figure 10 - Uplink DPDCH and DPCCH Slot

4. EVM Testing of WCDMA Devices

Verification of WCDMA performance standard test signals have been defined by 3GPP Test Specification 34.121. This incorporates models for testing the multiple operating modes inclusive of HSPA. Three measurements are defined and utilized for EVM testing. These include a QPSK and composite EVM measurements to address both HSDPA and HSUPA.

Each of the test signals described is available as a standard test model for generation in Agilent Signal Studio. By selecting the appropriate Test Model (TM) within Agilent Signal Studio N7600B, 3GPP WCDMA, the user can generate waveforms which can be directly downloaded to both the Verigy 93000 Port Scale RF modulated stimulus or MCB AWG waveform setup for baseband testing. Utilization of bench instrumentation to validate test signals prior to utilization in ATE can be a valuable tool to help understand the necessary test setup and ensure correlation of the ATE setups. Each test waveform generated and described with Agilent Signal Studio is validated with a loopback between an Agilent E4438C modulated signal generator and an E4440A Power Spectrum Analyzer with Agilent 89600 Vector Signal Analyzer. The generated and validated waveform files can then be directly downloaded directly to the Verigy 93000 Baseband and RF waveform generators for use in ATE testing.

4.1 QPSK EVM

A signal with a single DPDCH (or a single DPCCH) maps onto a simple QPSK constellation. A signal with a DPDCH and a DPCCH at the same amplitude level maps onto a 45°–rotated

QPSK constellation. Because the receiver does not care about the absolute phase rotation, it effectively sees a QPSK constellation.

The QPSK EVM is a simplified measurement of the performance of the baseband filtering and RF modulation. As it does not descramble and despread the signal it does not detect Spreading Code (OVSF) or complex scrambling errors.

The QPSK EVM waveform generation is developed through the use of Signal Studio by selecting Test Model 4. This test model generates a signal with three channels allocated. Channel 1 is defined as 15ksps P-CCPCH with random data. Channel 2 is 15 ksps PSCH. Channel 3 is 15ksps SSCH. This is demonstrated in the channel allocation in Figure 11 - Test Model 4 - Code Domain Power. The Code Domain Power (CDP) graph is a normalized distribution of the signal power across the individual channels. Figure 11 demonstrates the minimal content of this test model as it is limited to only 3 of the available channels.

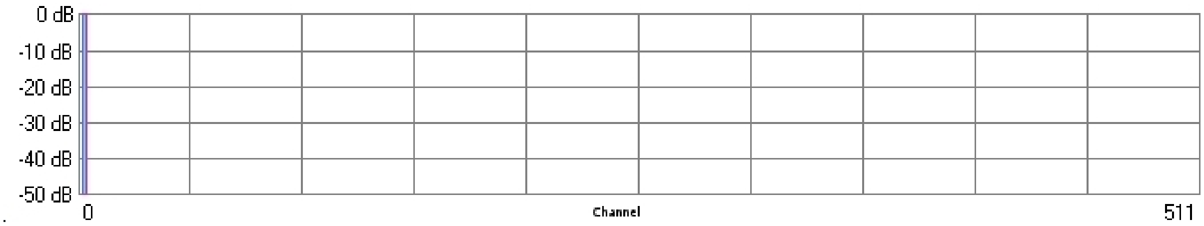

Figure 11 - Test Model 4 - Code Domain Power

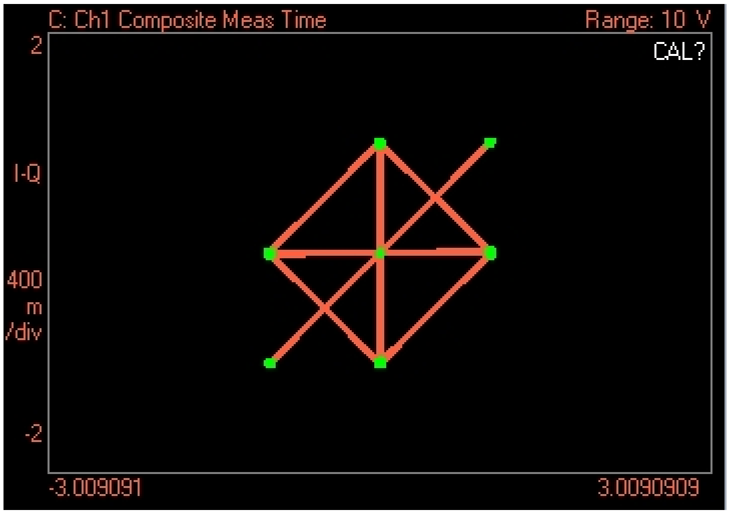

Figure 12 - Agilent 89600 Test Model 4 Constellation - E4438C to E4440A Loopback

Utilizing a bench loopback for analysis of the Agilent Signal Studio generated signal demonstrates the results seen in Figure 12 - Agilent 89600 Test Model 4 Constellation - E4438C to E4440A Loopback. As is demonstrated, the resulting constellation is a simple rotated QPSK.

4.2 Composite EVM

Measurement of QPSK EVM for a signal with a single DPDCH (QPSK EVM) does not fully address the quality of the transmitter for any possible channel configuration. The constellation of a signal will vary depending on its channel configuration. The utilization of multiple channels with a variety of definitions and power is composite EVM. Composite HSDPA can be developed by generating the appropriate standards compliant waveform using Agilent Signal Studio Test Model 5. This develops a waveform which includes a configuration of 46 defined channels of varying power and rates per channel ranging from 15ksps to 240ksps. The complexity of this signal is demonstrated in Figure 13 - Test Model 5 - Code Domain Power. Note that this figure clearly demonstrates the rate of each channel. As is evident the majority of the channels are at 30ksps as indicated by the narrow channel width. Eight channels are high rate, 240 ksps, as demonstrated by the large blocks in the CDP.

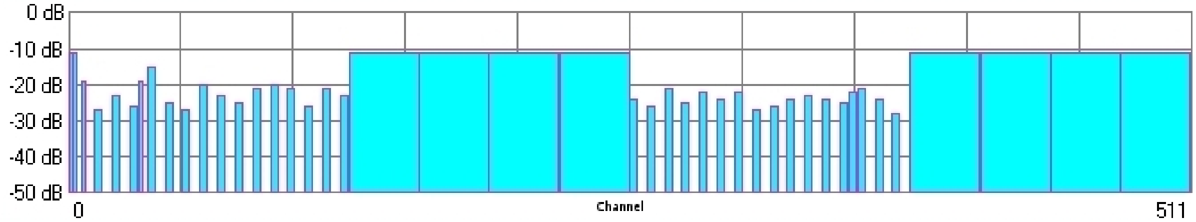

Figure 13 - Test Model 5 - Code Domain Power

Demodulation of the generated Test Model 5 signal using a loopback is demonstrated in Figure 14 - Agilent 89600 Test Model 5 Analysis - E4438C to E4440A Loopback.

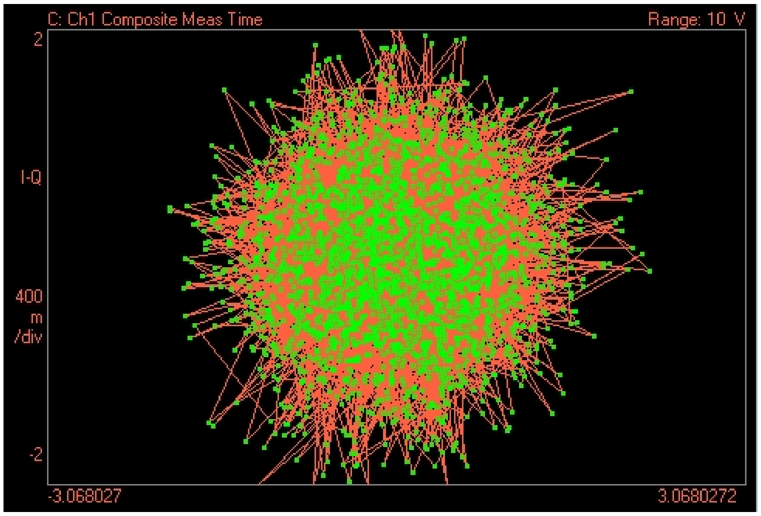

Figure 14 - Agilent 89600 Test Model 5 Analysis - E4438C to E4440A Loopback

For a regular QAM or a PSK signal, the ideal symbol points always map onto a few specific locations in the I/Q plane. However, the WCDMA UL signal can consist of multiple channels that are I/Q multiplexed. This means the bits for each channel are binary phase shift keying (BPSK) encoded for either the I or the Q paths. Several channels can be added to the I and/or the Q paths. The resulting I and Q signals are then spread and scrambled with a special function (HPSK). The resulting constellation depends on the physical channel configuration. The constellation typically does not look like QPSK, or any other known constellation, except for some very specific channel configurations.

The model utilized for testing the HSUPA EVM is composed of 5 channels with data rates varying from 15ksps to 960ksps using the R7 subtest 1 test model. The channel allocation is demonstrated in Figure 15 - HSUPA Channel Domain Power. Note, as indicated in the Uplink portion of the Protocol review, the high sample rate (960ksps) user data is transmitted on the I path of the modulator. The resulting constellation is demonstrated in Figure 16 - 89600 HSUPA Analysis - E4438C to E4440A Loopback

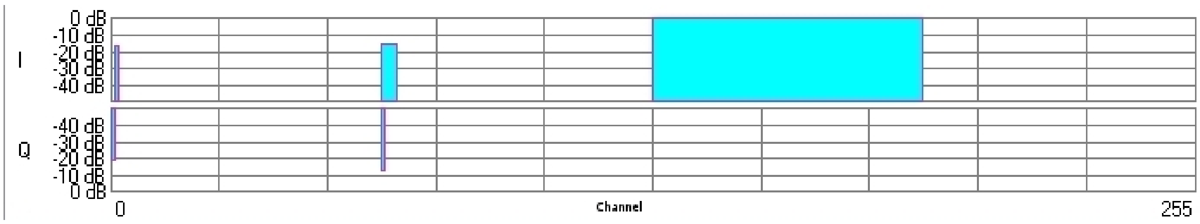

Figure 15 - HSUPA Channel Domain Power

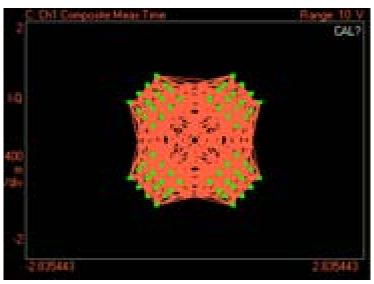

Figure 16 - 89600 HSUPA Analysis - E4438C to E4440A Loopback

5. Conclusion

WCDMA provides significant flexibility to provide support of multiple users at independent data rates. This flexibility necessitates the utilization of multiple complex waveforms for validation and test. Understanding the building blocks of the waveforms from both a protocol and physical perspective will help ensure the development of effective test setups and provide the knowledge necessary to troubleshoot unexpected results. The direct leverage of the waveforms utilized for bench testing to ATE will ensure a successful, timely implementation and correlation.

6. References

[1] Smith, Collins, *3G Wireless Networks*, 2^{nd} Edition. McGraw Hill, 2007.
[2] wikipedia.org – UMTS Frequency Bands
[3] “Innovations in WCDMA”, *Ericsson White Paper*, 284-23-3113, March 2008

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