
<3rd generation CDMA wireless systems>

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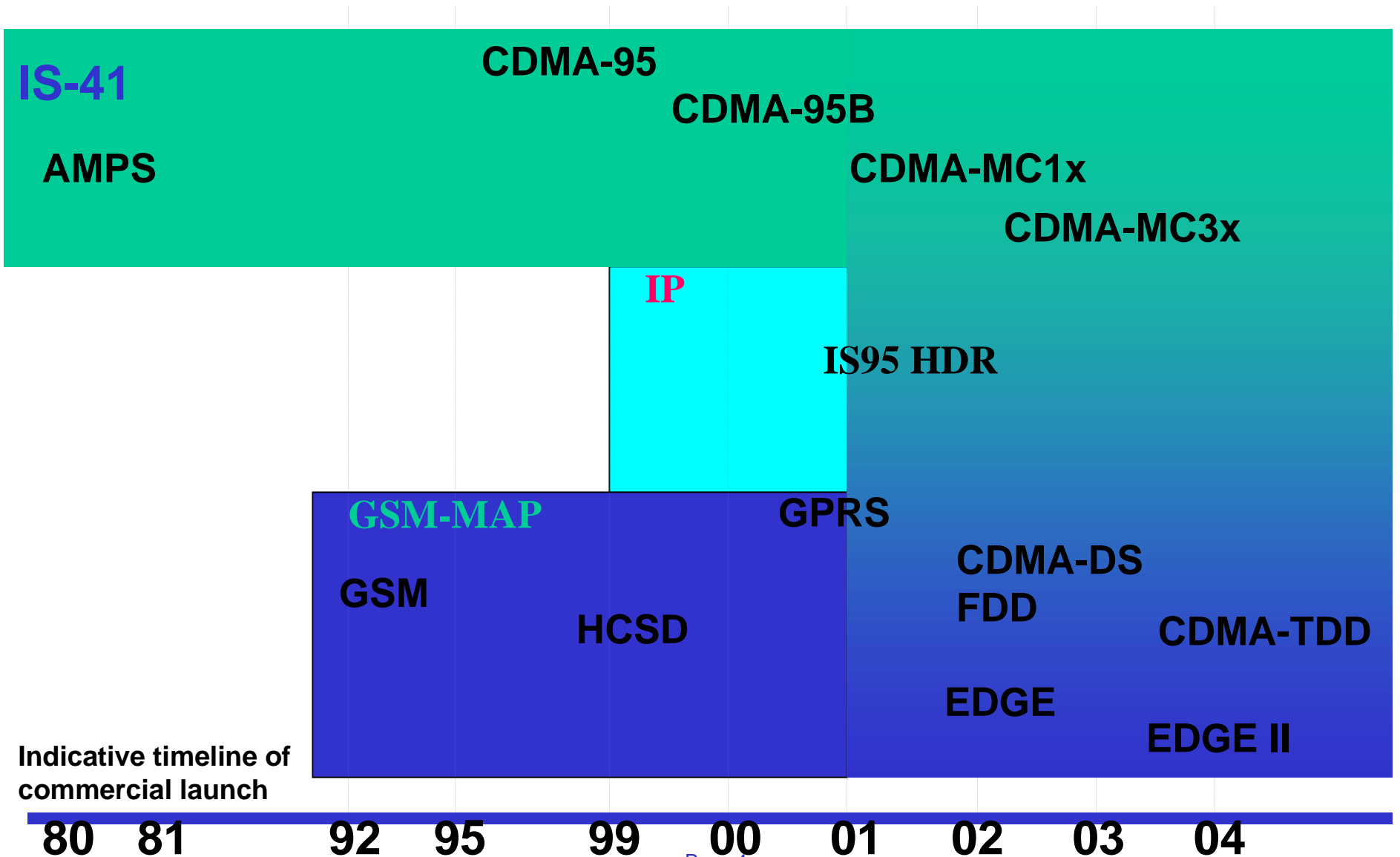
Overview

- What is 3G ?
- A brief overview of IS95
- Key design choices for CDMA 3G systems.
 - Bandwidth
 - Modulation
 - Coding
 - Power Control
 - Transmit Diversity
 - Base Station Synchronization.
 - Acquisition
 - Beam Forming
 - Multi-user detection
 - Peak To Average Power
- Objective is not to provide detailed justifications, but instead provide some insight into the level of optimization that went into designing the physical layer of the next generation wireless systems.

What is 3G ?

- A loosely defined term referring to next generation wireless systems.
 - Analog was 1G. GSM/IS95 were 2G. Next is 3G.
- Used interchangeably with IMT2000 although there are some specific IMT2000 guidelines defined by the ITU.
- Envisioned as a single Global standard allowing seamless roaming across the world.
 - Market is expected to be fragmented amongst several competing standards.
 - Mostly dominated by Direct Sequence CDMA.
 - Marketed as Global 3G CDMA implying a single unified standard. In reality, Global 3G comprises of 3 modes :
 - » Multi-carrier CDMA FDD
 - » Direct Spread CDMA FDD
 - » Direct Spread CDMA TDD
 - There are others : IS95 HDR, EDGE, etc.

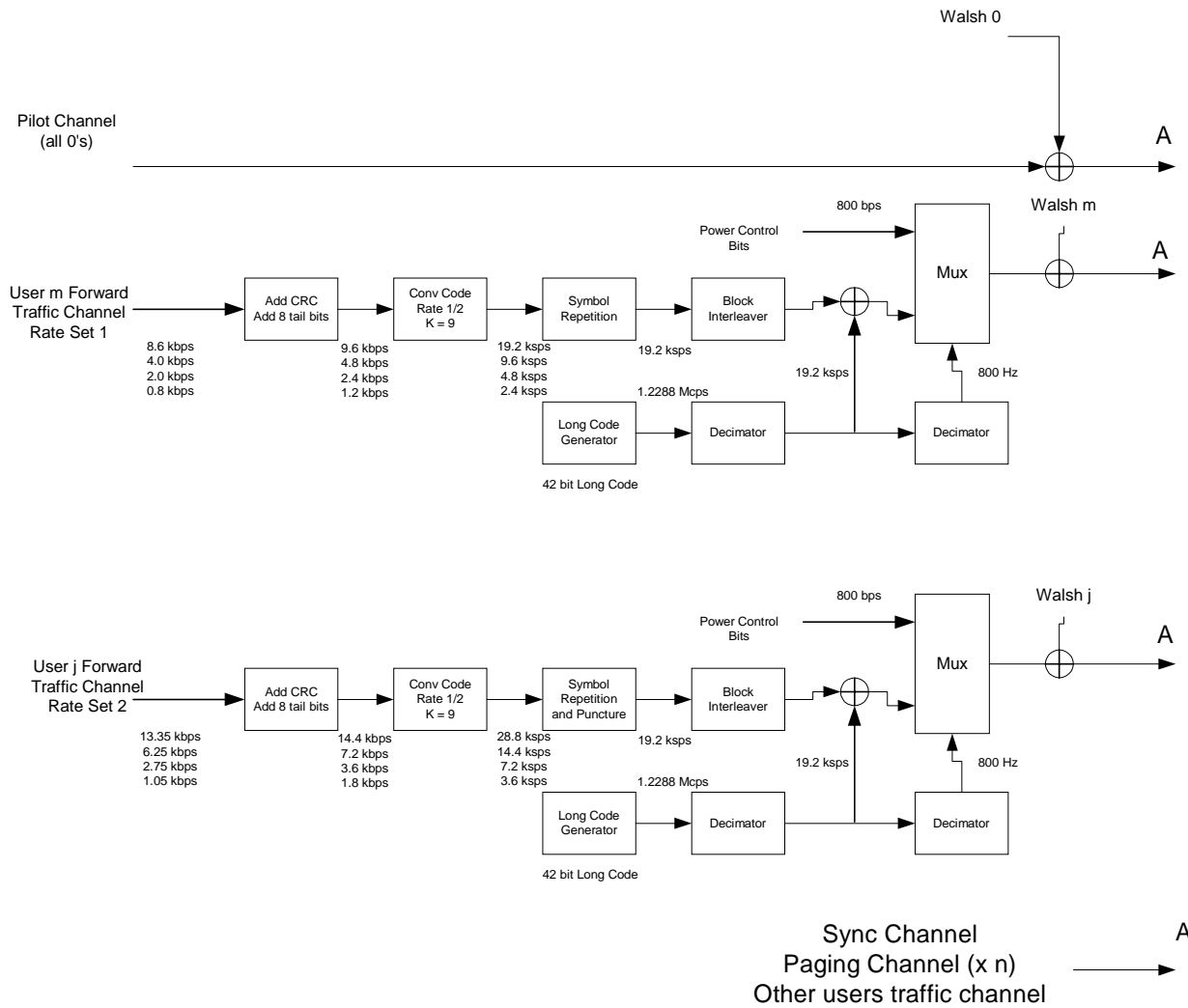
The Big Picture



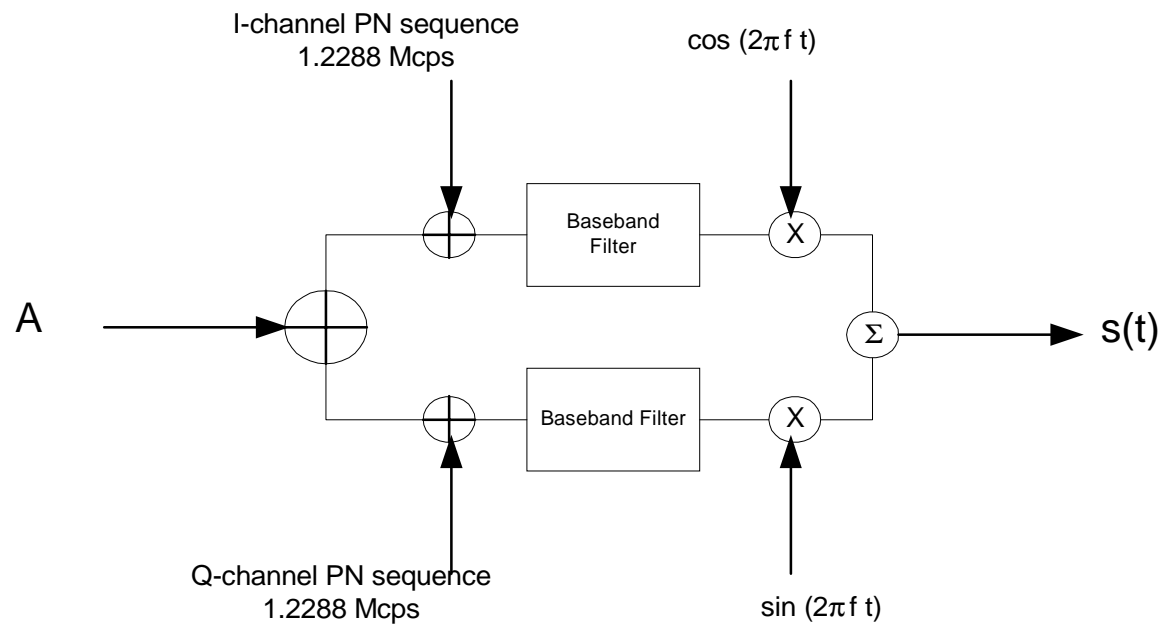
Indicative timeline of commercial launch

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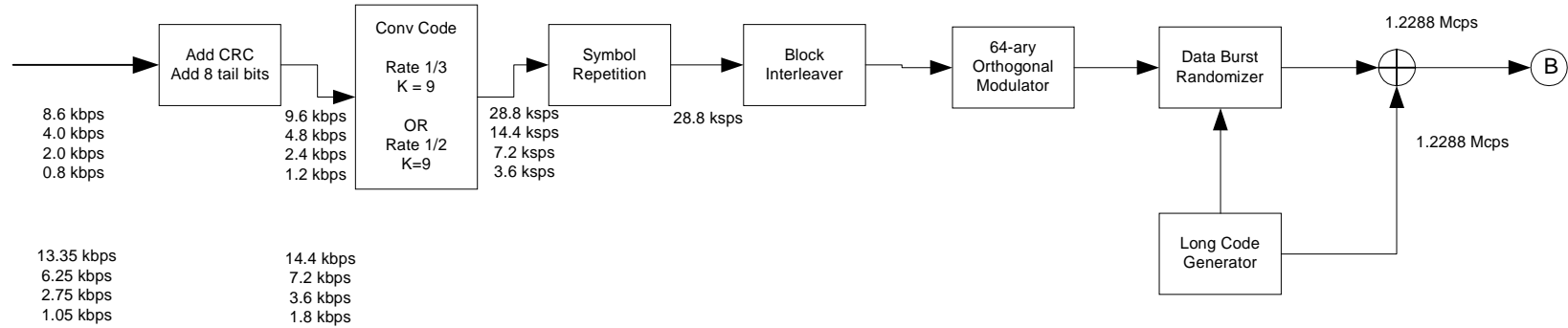
IS95 Forward Link (BS to mobile)



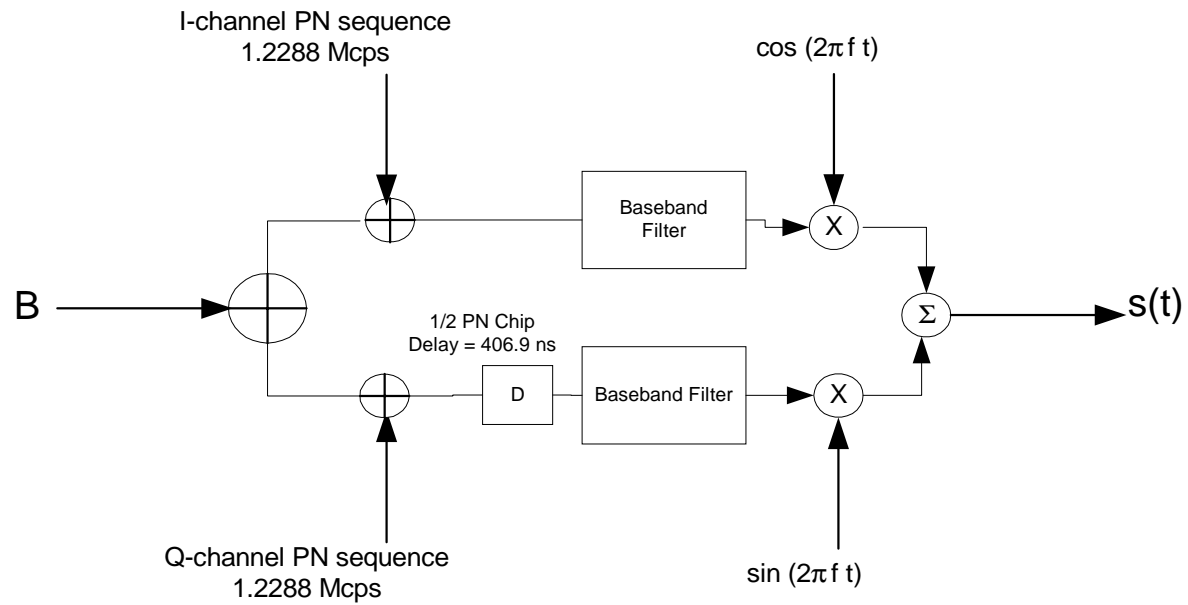
IS95 Forward Link (contd.)



IS95 Reverse Link (Mobile to Base Station)



IS95 Reverse Link (contd.)

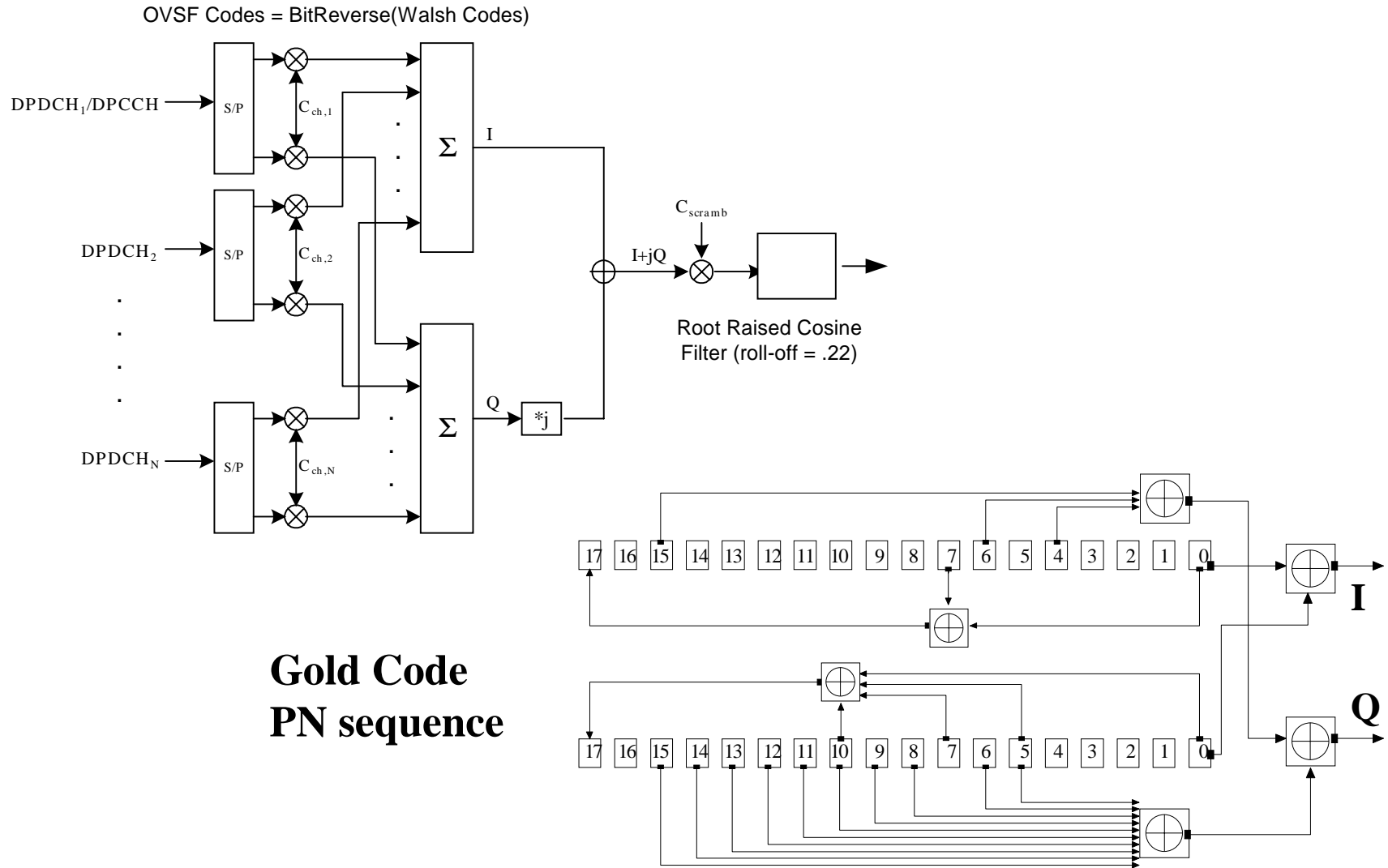


3G CDMA

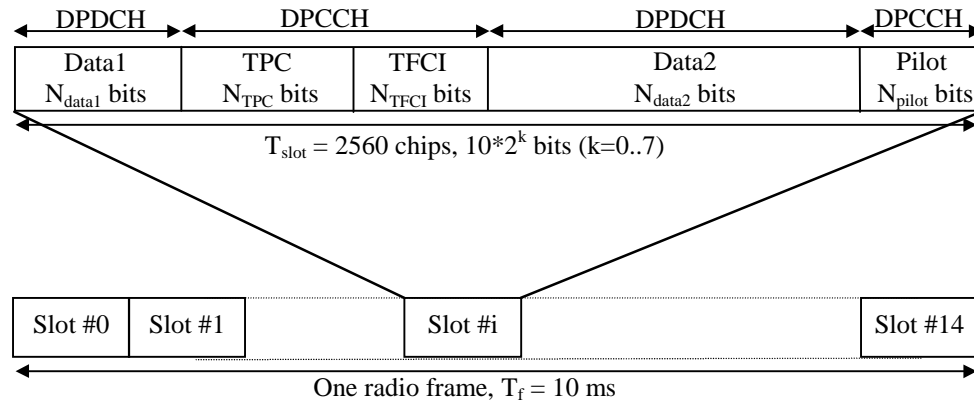
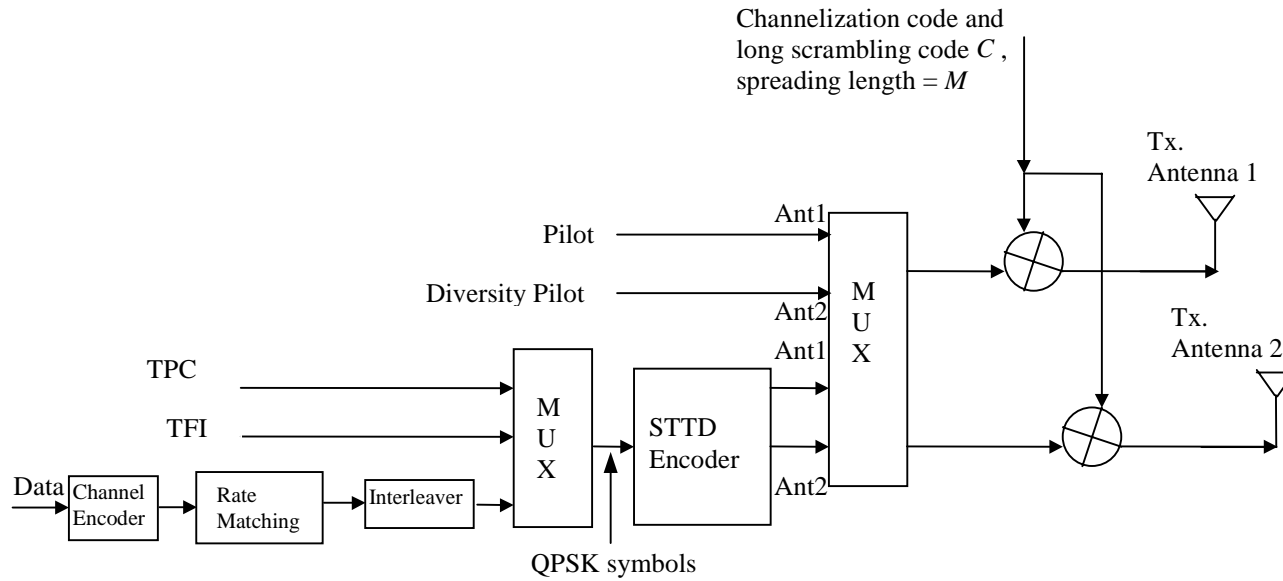
3G Standards

- Focus on 2 systems
 - WCDMA FDD and CDMA2000
 - Expected to be the dominant 3G standards, although IS95 HDR is gaining popularity.
 - HDR is a data only system.
- WCDMA (CDMA-Direct Sequence)
 - Strongly pushed by ETSI (Europe) and ARIB (Japan)
 - CDMA Air interface (3.84 Mcps), GSM protocol stack.
 - NTT DoCoMo (under pressure from IS95 deployment by DDI/IDO in Japan) is targeting initial deployment in Fall, 2001.
- CDMA2000 (CDMA - Multicarrier)
 - An evolution over IS95
 - Two versions : 1x (1.2288 MHz) and 3x (3 carriers at 1.2288 MHz each)
- There seems to be little debate on which system has higher capacity (as technically, the two systems are very similar)
- Success depends largely on cost, time to market and political factors.
- Focus of this talk is on Physical Layer

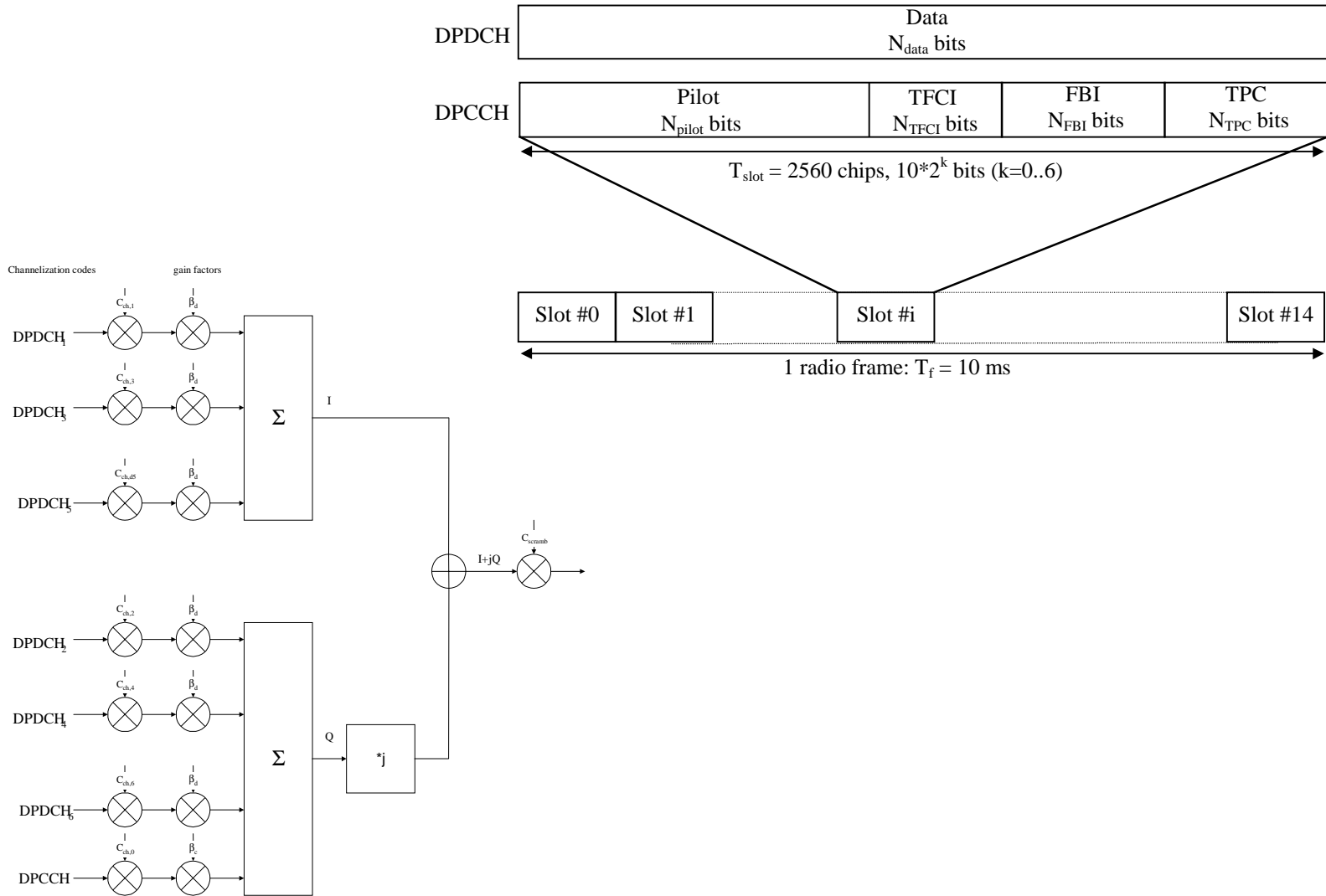
WCDMA Forward Link



WCDMA Forward Link



WCDMA Reverse Link



Bandwidth

- Both systems support wider bandwidth.
- Biggest advantage is ability to support higher peak rates.
 - Although HDR supports the same peak rates in a 1.25 MHz channel.
- Other advantages (increased frequency diversity, better interference statistics, etc.) have not been properly quantified.
- The disadvantage is increased design complexity
- WCDMA has a bandwidth of 3.84 Mcps. Big PR effort against IS95 : *Wideband vs Narrowband* CDMA.
- CDMA2000 1x is the same as IS95. 3x MultiCarrier is 3.6864 Mcps.
- Both WCDMA and CDMA2000 3x MC support data rates around 2 Mbps.
 - Only a single user (in good channel conditions) / sector can be supported at these rates, i.e. high rate service is not going to be cheap !

Modulation

- Reverse Link
 - IS95 used 64-ary orthogonal modulation
 - » This allowed non-coherent demod at the receiver. Coherent demodulation at receiver was considered risky.
 - » Peak data rate (i.e. 14.4 kbps) was much lower than the signal bandwidth (1.2288 Mcps).
 - » Assumed a conventional receiver (i.e single user CDMA receiver) at the base station. This implies that primary objective is to reduce transmit power at the mobile.
 - » So, with this system, objective is to use the best (given the constraints of implementation complexity) rate $1/p$ code, where p = processing gain.
 - » IS95 used a convolutional code (rate $1/2$ or $1/3$) followed by a (6,64) orthogonal block code, followed by a repetition code.

Modulation

- Forward Link
 - IS95 used BPSK because
 - » More tolerant to phase errors. Performance in fast fading channels was a concern.
 - » General view was that IS95 was interference limited and hence more efficient modulation was not necessary.
 - Clearly, increased bandwidth would have allowed more powerful lower rate codes, and hence could have increased capacity.
 - In benign channel conditions (e.g. wireless local loop), the number of available walsh channels was limiting forward link capacity.

Modulation

- 3G
 - WCDMA, CDMA2000 : both are going for QPSK modulation (on both links) with pilot for phase reference.
 - » Increased capacity, lower rate codes.
 - » Coherent demodulation not perceived as a problem. In fact, the overhead of pilot on the up link more than compensated by improvements in synchronization and power control.
 - » Supporting higher data rates. Hence, there is insufficient processing gain for 64-ary orthogonal modulation.
 - HDR is using adaptive modulation (upto 16 QAM) and adaptive processing gain to improve capacity.

Coding

- IS95
 - Convolutional codes only.
 - Rate 1/2 or 1/3 on uplink, $K = 9$.
 - Rate 1/2 or 3/4 on downlink. The rate 3/4 code is used for the highest data rate (14.4 kbps), and is not a good code ...
- 3G
 - Same conv codes for CDMA2000, WCDMA and HDR, except that the rate 3/4 code has been removed and a rate 1/3 code on the downlink has been introduced.
 - Turbo Codes for data.
 - » CDMA2000 and WCDMA use the same parallel Concatenated Codes. $K = 4$, rate 1/3. The turbo interleavers are different
 - » HDR : Serial Concatenated codes. $K = 5$, rate 1/2 outer code followed by $K = 3$, rate 1/2 inner code

Power Control

- IS95
 - Fast Reverse Link Power Control at 800 Hz
 - Very slow Forward Power Control
 - » IS95 A forward power control was a few Hz.
 - » IS95 B increased it to 50 Hz
 - Slow Forward Power Control big limitation.
 - In order to guarantee voice quality, base station has to put a floor on minimum transmit power.
 - Generally, the forward link is the capacity limiting link.
- 3G
 - CDMA2000 uses 800 Hz for both uplink and downlink.
 - WCDMA uses 1500 Hz for both links.
 - Improved forward power control has a significant improvement on system capacity.
 - HDR uses rate control instead of power control.

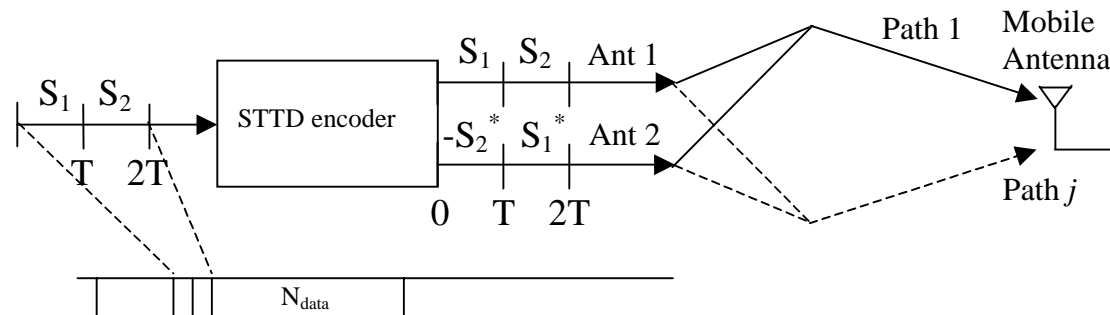
Transmit Diversity

- No transmit diversity for IS95
- CDMA2000 uses 2 forms:
 - OTD : Orthogonal Transmit Diversity.
 - » Transmit consecutive symbols on adjacent antennas using orthogonal codes.
 - STS : Space Time Spreading
 - » Ant 1 : $S1 \times W1(t) - S2^* \times W2(t)$
 - » Ant 2 : $S1^* \times W2(t) + S2 \times W1(t)$
 - » $W1(t)$, $W2(t)$ are orthogonal sequences.
- WCDMA supports several forms of Transmit Diversity
 - STTD : Space Time Transmit Diversity
 - » Ant 1 : transmit $S1 \quad S2$, $S1$ & $S2$ are complex symbols
 - » Ant 2 : transmit $-S2^* \quad S1^*$
 - » For STS & STTD, performance equivalent to two antenna receive diversity in flat fading environment.

Transmit Diversity

- Feedback Mode Transmit Diversity
 - » WCDMA provides fast feedback (upto 1500 Hz) mode transmit diversity.
 - » Allows receiver to control the amplitude and phase of the two antennas.
- Time Switched Transmit Diversity
 - » Signal is transmitted alternately from two antennas using predetermined pattern.

STTD



Base Station Synchronization

- CDMA systems generally have a frequency reuse factor of 1, and hence do not require any frequency planning.
- However, they do need to do code planning in order to ensure that they do not allocate the same PN codes to adjacent base stations.
- In IS95 and CDMA2000, different base stations use a different offset of the same PN sequence.
 - Base stations are synchronized using GPS. Hence, having different offsets ensures that the PN sequences from different base stations will not coincide with one another. The offsets are at a minimum of 256 chips apart.
- WCDMA does not require synchronization.
 - Mostly a political issue as some governments do not want to have their communications infrastructure rely on a US defense program.
 - Once again, this was a big PR effort against IS95 & CDMA2000.
 - Most of the initial deployments are expected to be in synchronous mode.

Base Station Synchronization

- Async. Systems cannot use offsets of the same PN sequence for different base stations and hence we need an efficient way to generate multiple PN sequences.
- WCDMA uses Gold codes for PN sequences. Gold codes are constructed as linear combinations (in GF(2)) of two m-sequences.
 - Cyclic shifts of one sequence with respect to another create different codes.
 - IS95 & CDMA2000 use an m-sequence (i.e. maximal length LFSR) for generating the PN sequence.
- Asynchronous base stations have some problems :
 - Initial Acquisition
 - » Instead of searching for a single PN sequence, with async. Systems, the mobile has to search for multiple PN sequences.
 - Handoff searching.
 - » Every handoff search is like initial acquisition.
 - » In contrast, for sync. Systems, handoff searching is simpler. E.g. for IS95, the initial acquisition window size is 2^{15} chips. For handoff searching, the uncertainty is much less (= max delay spread)

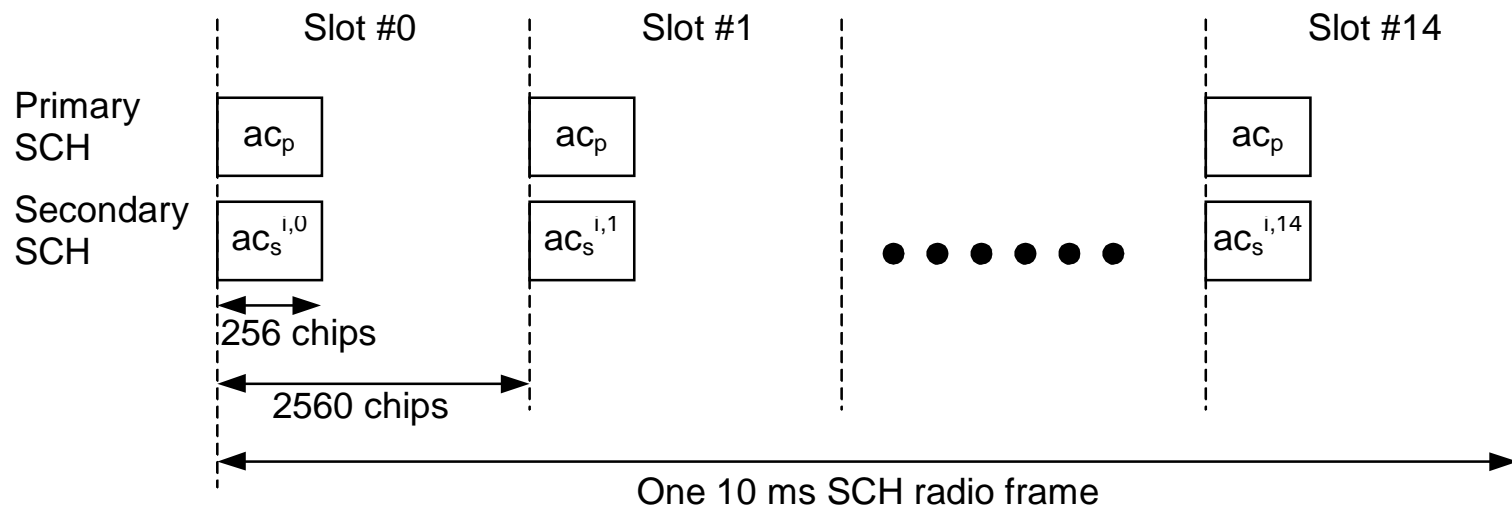
Acquisition

- Fast acquisition is very important for a mobile user in a multi-cellular environment.
 - Even more important for CDMA systems where minimizing transmit power to close the link is a key determinant of system capacity.
 - So, phone should always try to lock onto the strongest pilot.
- CDMA2000 uses a continuous pilot like IS95.
- WCDMA uses a 3 step hierarchical search process to reduce acquisition time.

WCDMA Searching

- Total of 512 Gold Codes divided into 64 groups of 8 codes each.
- In addition, there are 2 Synchronization sequences, SCH1 and SCH2.
- SCH1 is a 256 chip PN code common to all base stations. Repeats every slot (1 slot = 2560 chips)
- SCH2 can be one of 16 different sequences. Code length is 256 chips and it is time aligned with SCH1. Sequence length is 15 slots (10 ms).
 - Sequence is sub-set of a Reed Solomon Code.
 - Comma Free Property. That means, no cyclic shift of a code is a valid code.
 - So, receiver can unambiguously determine start of 15 slot sequence.
 - 64 different sequences, each representing one code group
- Step 1 : Use 256 chip match filter to determine modulo 'slot' (i.e. 2560 chips) timing.
- Step 2 : Identify code group and derive frame timing (10 ms timing)
- Step 3 : Exhaustive search against 8 possible codes in a code group.

WCDMA Synchronization Channel



Beam Forming

- IS95 only supports fixed sectorization.
- Beam Forming is considered important for 3G systems.
- All 3G systems (that I am aware of) support beam forming.
- Requirement is simple : Each channel with beam forming should have a dedicated pilot for phase reference.
- None of the systems provide a mechanism for the phone to provide the CSI (Channel State Information) to the transmitter (with the exception of Feedback Mode Transmit Diversity in WCDMA).
 - Beam form on remote scatterers
 - Have fixed spot beams for high capacity areas.

Multi-User Detection

- Does not seem to be much interest in multi-user detectors.
- A year ago, NTT was a big proponent of multi-user receivers, but lately there has been little development on that front.
- Biggest problem is designing multi-user receivers with reasonable complexity for a multi-cellular environment.
- WCDMA standard supports short spreading codes (256 chips as opposed to the regular 38400 chips) to aid in multi-user detection.
 - With long codes, the correlation matrix of the codes changes every symbol.
- Schemes such as interference cancellation do not require standards support.
- In IS95 the downlink was the capacity limiting link. With WCDMA & CDMA2000, the downlink capacity has been improved, but with asymmetric data rates, downlink may still be the capacity limiting link.
 - Having multi-user receivers on the base station would have little impact on capacity.

Peak To Average Power

- IS95 uses 2 schemes to reduce Peak To Average Power
 - Offset QPSK modulation to reduce Peak to Average.
 - Constant power transmission. For lower data rates, transmission is discontinued for some duration. The Peak to average remains the same; however, peak to average when the Power Amplifier is on is reduced.
- 3G
 - HPSK (Hybrid Phase Shift Keying)
 - » $c = c1 (w0 + j c2*w1)$
 - » $c1$ = PN sequence changing at chip rate.
 - » $c2$ = PN sequence changing at half the chip rate.
 - » $W0 = \{ 1 \ 1 \}$; $W1 = \{1 \ -1\}$
 - » phase transitions less than 90 degrees half the time.
 - Continuous transmission => worse peak to average
 - » Compensated by improved power control, time diversity and receiver synchronization.

Summary

Forward Link Capacity Improvements

- Fast Forward Power Control
- More spectrally efficient modulation
- Turbo codes and lower rate convolutional codes.
- Transmit diversity
- Dedicated pilots for support of beam forming.
- Support higher peak data rates.
- Protocol improvements to improve packet data transmission.

Summary

Reverse Link Capacity Improvements

- Coherent Reverse Link
- Improved synchronization and power control because of Reverse Link Pilot.
- Improved time diversity and power control because of continuous transmission.
- QPSK modulation
- Turbo codes
- Multi-user detection
- Faster Power Control (for WCDMA)
- Improved Access Channel
 - Reservation based schemes as opposed to slotted Aloha in IS95