

Homework Lessons?

What can we learn from the first deployment of OFDMA on HFC?

Hal Roberts, Calix

Started as a pure PON System

ADC Telecom proprietary PON named “Homeworx”

Based on British Telecom’s PON (built by BT’s manufacturing arm, Fulcrum)

- ▶ MAC used TDMA on a *bit interleaved* basis.
- ▶ PHY as same as EPON/GPON, OOK (on/off keying)

Designed to carry circuit switched traffic

- ▶ Telephony (DS0s) and ISDN

Trials with Pacific Bell circa 1990-1991

- ▶ RBOC interest in PON collapsed based on regulatory changes and desire to compete with cable operators for video

CableLabs/Time Warner Visit circa 1992

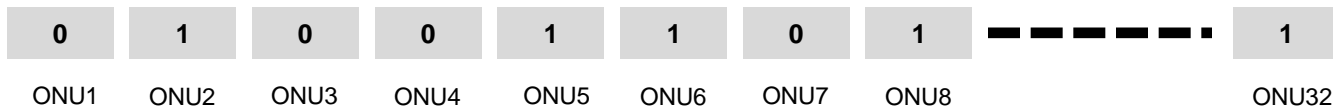
- ▶ Alexander Futro (CL) and David Pangrac (TW) visit ADC Homeworx lab looking for a solution for Voice over Cable
- ▶ ADC proposed converting optical transceivers in Homeworx PON to RF transceivers for HFC

Homework HFC “TDMA Phase”

Initial Approach

- ✦ Retain PON TDM/TDMA MAC
- ✦ Modify PHY layer only (*sound familiar?*)
- ✦ But Bit Interleaved MAC layer prevents EPoC style PHY

Bit Interleaved TDMA



- ✦ Eliminated any possibility of Multi-Bit Symbols, QPSK, QAM-16 etc.

RF Modulation “Solution”

- ✦ “Shaped” OOK
- ✦ Subject to: Group Delay and Multipath
- ✦ Leading to: Inter-Symbol Interference (ISI)



Successful Trial with Rochester Telephone

- ✦ ISI ‘fixed’ by deleting every other bit
- ✦ But used too much upstream bandwidth – 20MHz

Homework HFC “OFDM Phase”

Looking to go from worst spectral efficiency to first

MSOs cannot give 20MHz in Upstream

- ▶ Only 37MHz total and about 20MHz ‘clean’
- ▶ Spectral efficiency needed large improvement

Search for Efficient/Robust PHY led to OFDM

- ▶ OFDM allows carriers with no guard bands (efficient)
- ▶ Individual Sub-Carriers (Tones) mitigate Amplitude Ripple
- ▶ Cyclic Prefix mitigates Group Delay and Multipath
- ▶ Control Channels and Data can be on different Sub-Carriers with different QAM (for robustness)
- ▶ Long Symbol Durations mitigate Impulse Noise
 - FEC used for large/long impulse noise

Multipoint to Point OFDM on HFC led to first use of OFDMA

- ▶ OFDMA has significant efficiency advantages
- ▶ Required solving distributed synchronization problem

Homework Channel Model

Simple Model

Specification	Forward, Optics and Coax	Reverse, Optics and Coax
Maximum RF gain rate of change (without need for re-ranging)	<1dB / 1 sec	<1dB / 10 min.
Impedance	75Ω	75Ω
SNR	38 dB recommended	See Table "A"
CSO or CTB	-52 dBc recommended	N/A See narrow-band ingress table
Differential Group Delay over 6 MHz band	1.2us	1.2us
Narrowband Interference Levels, loss of SCs per interference spurs (without R-S error correction), "Loss" of SC defined as a BER of 1E-5. Interference levels below are measured with respect to single DS0 level. Narrowband is assumed to be <25kHz	Lost SCs	Lost SCs
+14 to +24 dBc	225	225
+4 to +14 dBc	70	70
-6 to +4 dBc	7-22	7-22
-16 to -6 dBc	3-7	3-7
-26 to -16 dBc	1-3	1-3
-36 to -26 dBc	0-1	0-1
Multipath	-10dBc @ 0.5us -20dBc @ 1.0us -30dBc @ 2.0us	-10dBc @ 0.5us -20dBc @ 1.0us -30dBc @ 2.0us
Common Path Distortion	See table for Narrowband Interference above	See table for Narrowband Interference above
Phase Noise	N/A assuming no block frequency conversion in the forward path.	<-70dBc/Hz@10Hz <-90dBc/Hz@100Hz <-94dBc/Hz@1kHz <-100dBc/Hz@10kHz <-130dBc/Hz@100kHz

Homework OFDM “Numerology”

6MHz OFDM Channel – 552 Sub-Carriers

- ✦ Required first 1024 pt. FFT custom ASIC

Symbol Duration

- ✦ 125 microseconds

Sub-Carrier Spacing

- ✦ 9kHz

Cyclic Prefix

- ✦ 12.5 microseconds (probably overkill)

Modulation

- ✦ BPSK, QAM-4 (QPSK), QAM-32

FEC

- ✦ Reed-Salomon
- ✦ 41 byte codeword
- ✦ ~ 20% Overhead

Homeworx Sub-Carrier Map

552 Subcarriers

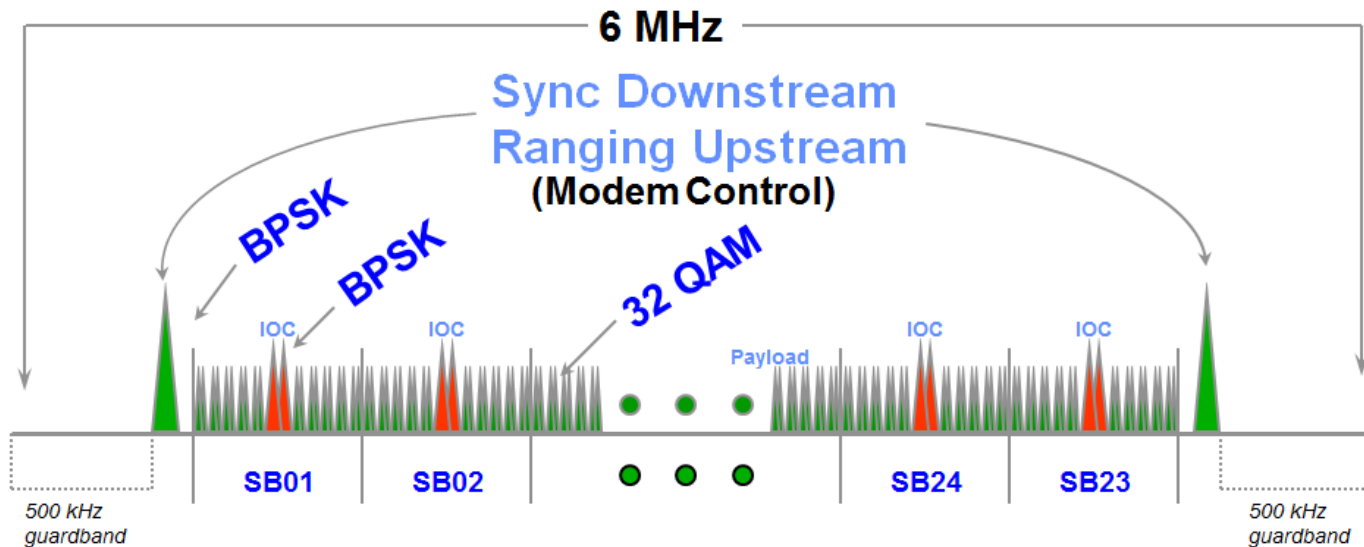
- Called 'tones' in this diagram

Payload, Control and Sync SCs

- Payload modulated at QAM-32 (later QAM-4 or QPSK)
- Control, Sync Modulated BPSK
- SCs were dedicated, payload, sync and control SCs did not switch

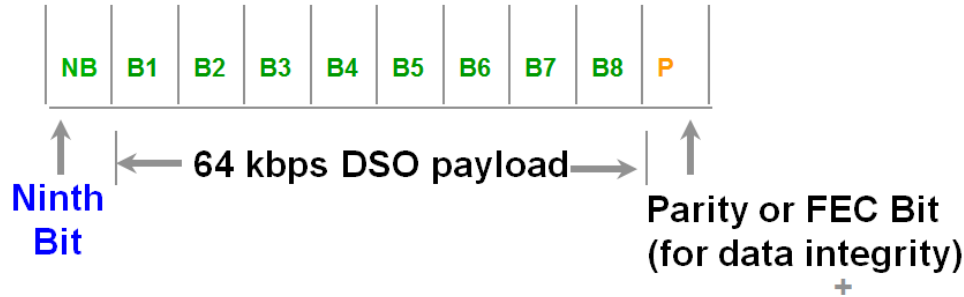
Rev 1 - Payload QAM-32 Only, no MCS

Rev 2 - Payload QAM-4/32 MCS (Called DC-OFDM "Dual Constellation")



Homework Frame Structure

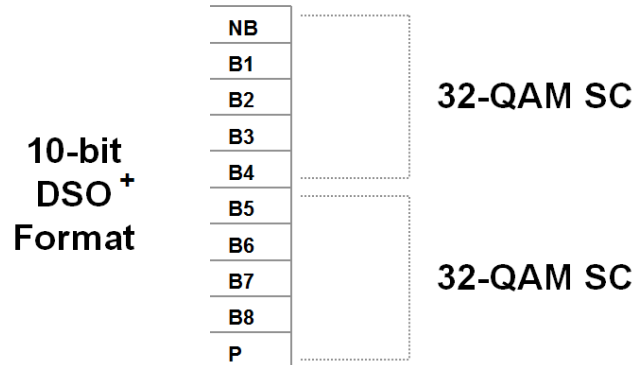
Frame in Time is converted to Frequency



8 Payload bits + NBS + Parity bit = 10 bit DSO format

Time →

Each QAM-32 signal can carry 5 bits of information



A complete, 10-bit DSO is carried by 2 32-QAM SCs

Frequency →

QAM-32 Constellation Map

Note: Upstream HFC at this time was QPSK at best

Upstream Downstream Rates Symmetrical

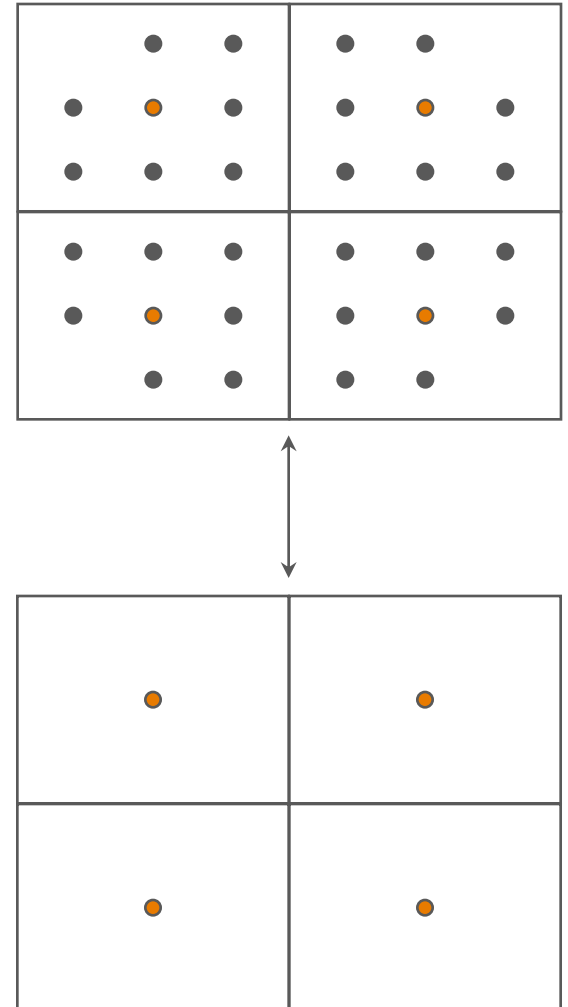
- ▶ QAM level based on upstream impairments
- ▶ QAM in DS based on US

QAM-32 in Homeworx

- ▶ QAM-32 (vs 16 or 64) used as two sub-carriers could carry 1 DSO + FEC/Signaling
- ▶ Predates QAM-16 in DOCSIS
- ▶ Highest upstream efficiency until DOCSIS 2.0 released Dec 2001

QAM-4 (QPSK) added for data channels circa 1999

- ▶ Called DC-OFDM for “Dual Constellation”



Homework Deployments

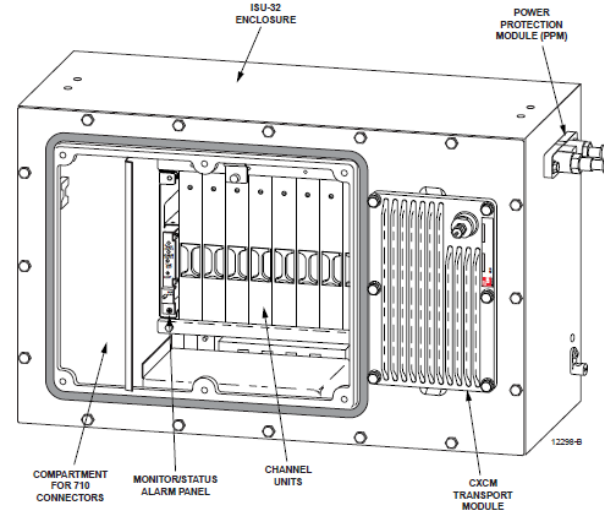
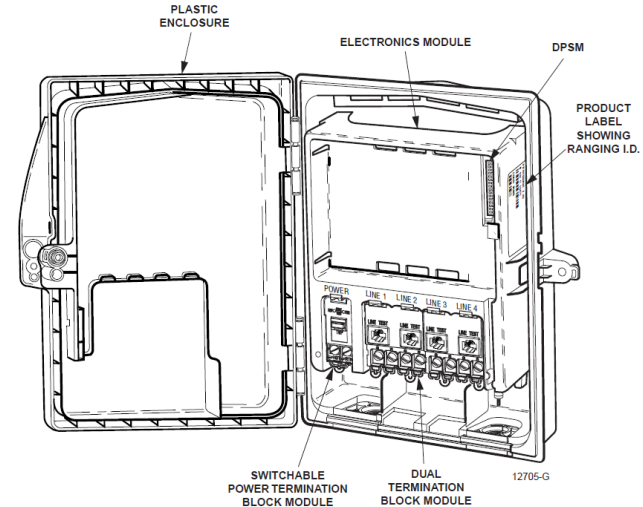
Starting in 1997 to ~2007

400K+ OFDM Modems (HISUs)

- ▶ > 1,000,000 Phone Lines

Customers

- ▶ Largest Operators
 - OptusVision
 - MediaOne/AT&T -> Comcast
 - Adelphia
- ▶ Smaller Operators
 - Wide Open West etc.



Why wasn't the first cable OFDMA a Commercial Success?

Fundamentally a Switched Circuit based platform

- ▶ World was moving away from switched circuit
- ▶ Switching to Packet Based required fundamental redesign of all cards

“Bleeding Edge” Technology

- ▶ FFT ASICs not available, required large number of custom ASICs
- ▶ Higher Cost due to lack of standardized volume components.
- ▶ Higher power consumption due to silicon technology status and relatively high digital signal processing
- ▶ QAM-32 seen as ‘fragile’, QAM-4 added late

Spectral Efficiency actually higher than needed

- ▶ Homeworx system allowed 240 simultaneous DS0s (phone lines)
- ▶ Consumers did not purchase multiple phone lines as expected
- ▶ “Take rates” did not equal operator’s expectations
- ▶ “Concentration” of phone lines reduces need for simultaneous channels

Homework Lessons?

Right Multiplexing, Wrong QAM Level

- ✦ OFDM using QAM-4 (first) would have been ideal choice
- ✦ Faster time to market
- ✦ Lower cost
- ✦ Lower power
- ✦ Add QAM-XX Later

Great pressure to add multiple modulations for higher plant noise (security blanket)

- ✦ QAM-4 added to QAM-32 for payload at high development cost
- ✦ Operators *never* turned on QAM-4

Modems were 'Right Sized'

- ✦ Single-family unit demodulated and transmitted only 1/20th of 6MHz channel
- ✦ Multi-family unit demodulated and transmitted 1/2 of 6MHz
- ✦ Saved power and cost

Homeworx Lessons?

Too many resources associated with one 6 MHz headend channel which could not be redistributed

- ✦ Low take rate plants still consumed entire headend modem resources
- ✦ Flexible distribution of resources essential
- ✦ Ideal (for the time period) would be 2MHz per channel

No issues with Multipath or Group Delay

- ✦ Cyclic Prefix of 12.5us eliminated impact of distortions
- ✦ But 12.5us is probably too good (long) in retrospect

Complexity

- ✦ Complex system (for its time)
- ✦ KISS



Calix

ACCESS INNOVATION