Homeworx Lessons?

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

Hal Roberts, Calix

Supporters

Eugene Dai – Cox Communications

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

Homeworx 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

0	**1**	**0**	**0**	**1**	**1**	**0**	**1**	- - - - - - ·	**1**
ONU1	ONU2	ONU3	ONU4	ONU5	ONU6	ONU7	ONU8		ONU32

- 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

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Homeworx 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

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Homeworx 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 +14 to +24 dBc +4 to +14 dBc -6 to +4 dBc -16 to -6 dBc -26 to -16 dBc -36 to -26 dBc	Lost SCs 225 70 7-22 3-7 1-3 0-1	Lost SCs 225 70 7-22 3-7 1-3 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

Homeworx 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 (IOC) and Sync SCs

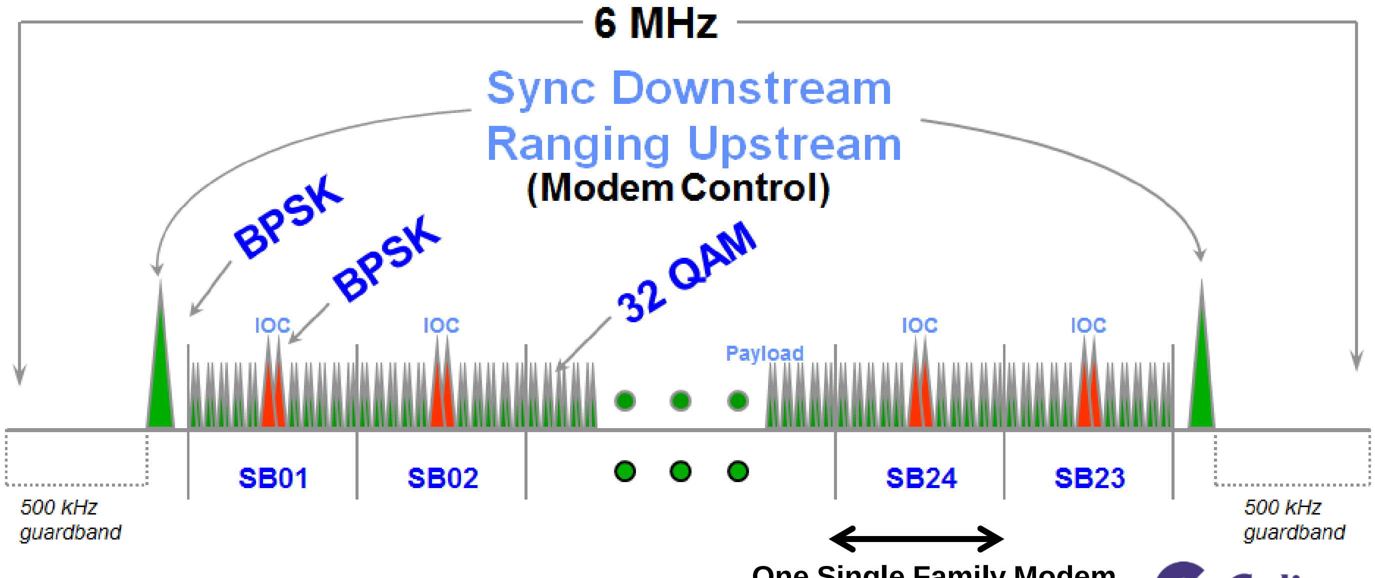
- Payload modulated at QAM-32 (later QAM-4 or QPSK)
- Control, Sync Modulated BPSK
- SCs were dedicated, payload, sync and control SCs did not switch

Rev 1 - Payload QAM-32 Only, no MCS

Rev 2 - Payload QAM-4/32 MCS (DC-OFDM or “Dual Constellation”)

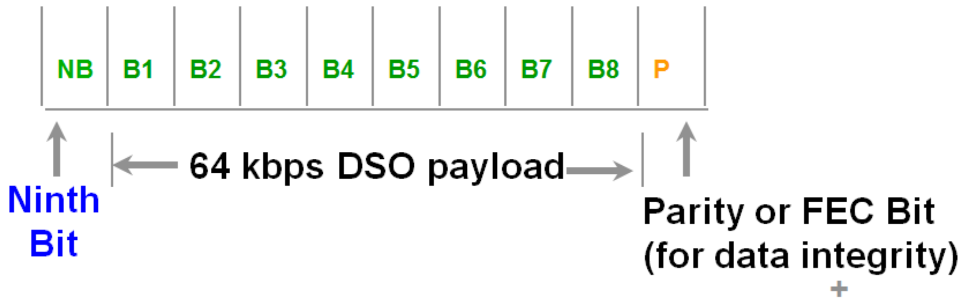
Max OFDMA Tx

- 240 simultaneous Remote transmitters



Homeworx Frame Structure

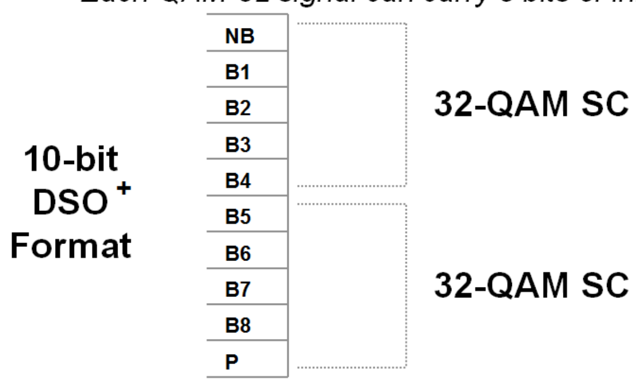
Frame in Time is converted to Frequency



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

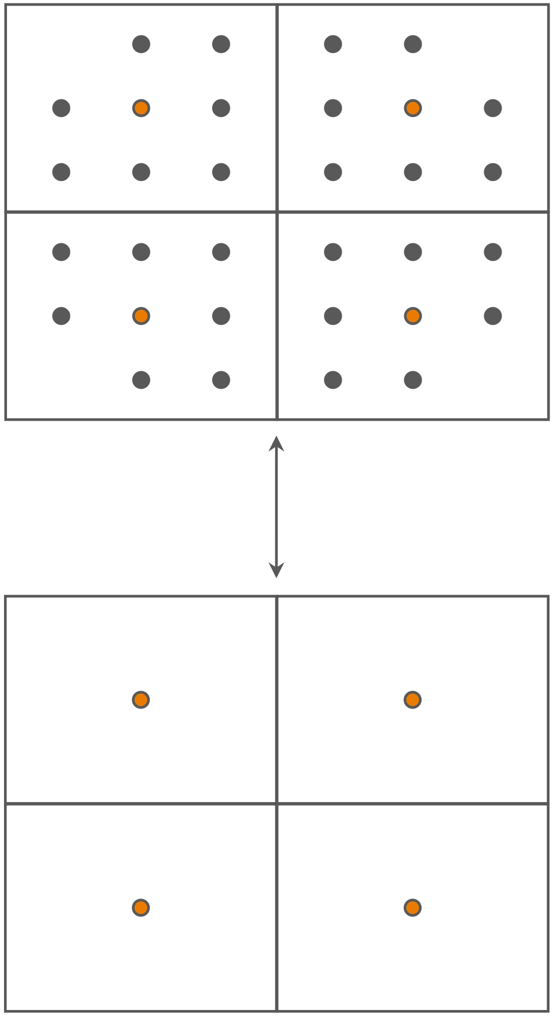
- QAM level based on upstream impairments
- QAM in DS based on US

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”



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Scanning and Synchronization

Remote modem scanned every 2 MHz till OFDM sync detected

- Covers both 6 MHz and 8 MHz plans

Symbol Rate and Channel Frequency are locked at Headend Modem

- When remote modem locks to

Two ‘Sync’ Channels in the Downstream

- BPSK - Separated from Data Channels for fast Sync
- Two for redundancy, if Primary had ingress go to Secondary
- Synchronization of Carrier Frequency/Symbol Rate are done on Sync tone
- Derotation of BPSK to adjust phase
- Remote goes to predefined IOC (ISU Operations Channel) to track via keeping BPSK in phase in I/Q plane

Ranging

Downstream and Upstream Carriers Locked at Headend

- Therefore once the Remote modem is downstream synced, upstream is automatically locked (no Doppler shift to be concerned with)

Ranging

- For amplitude and phase adjustment only
- Remote transmitter uses one of two upstream ranging subcarriers
- Ranging SC is separated from Data SCs (not orthogonal until ranging)
- Amplitude is adjusted in coarse and fine steps
- Phase offset measured and Headend modem transmit phase offset to Remote modem
- Derotation of BPSK and QAM-32 done and tracked in headend modem reciever

Periodic Amplitude and Phase Adjustment

- Done via IOC transmissions on periodic basis.
- All OFDMA carriers are transmitted at the same level from remote (i.e. no amplitude equalization).

Homeworx Deployments

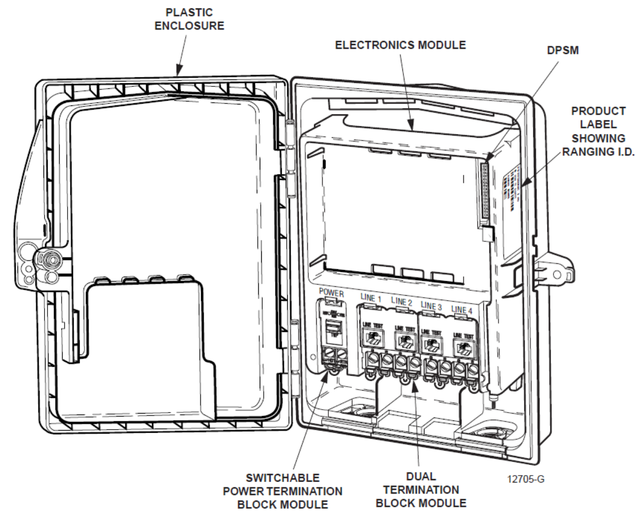
Starting in 1997 to ~2007

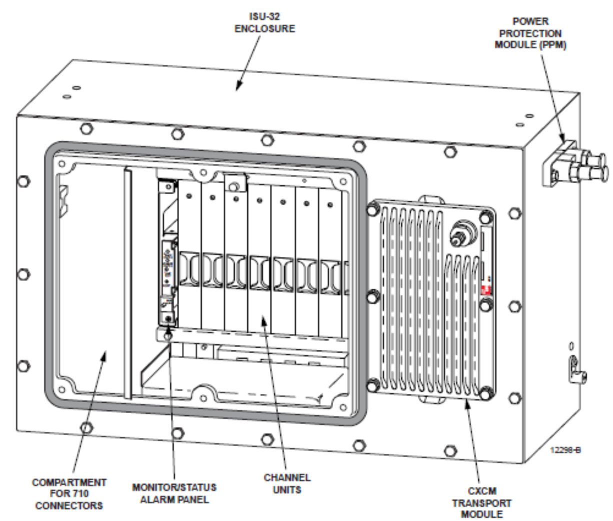
400K+ OFDM Modems (HISUs)

- > 1,000,000 Phone Lines

Customers

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





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Why wasn't the first cable OFDMA system 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

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Homeworx 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 ½ 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