Introduction to ADSL Modems

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http://www.ece.utexas.edu/~bevans/projects/adsl

Outline

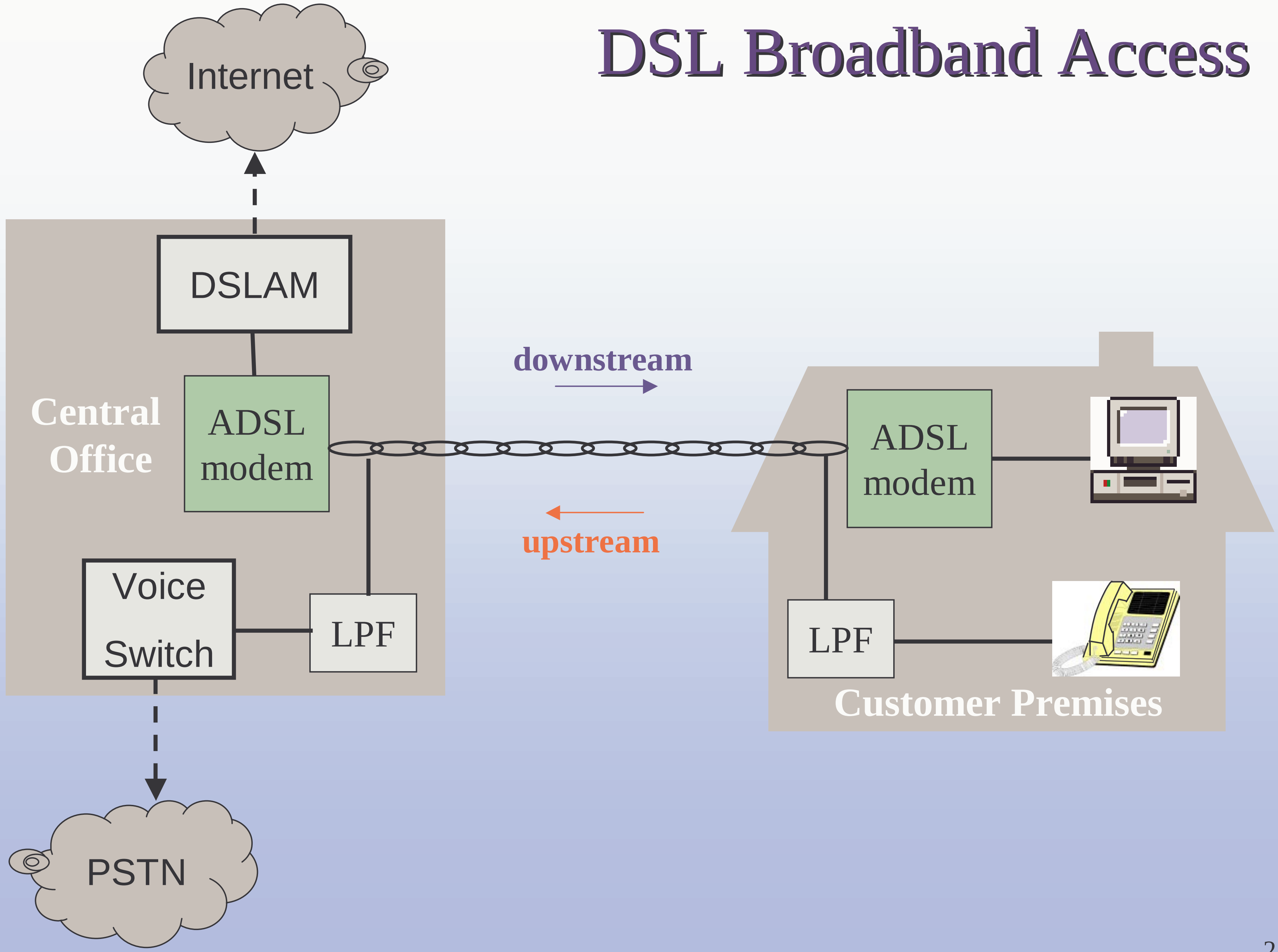
- **Broadband Access**
  - Applications
  - Digital Subscriber Line (DSL) Standards
- **ADSL Modulation Methods**
  - ADSL Transceiver Block Diagram
  - Quadrature Amplitude Modulation
  - Multicarrier Modulation
- **ADSL Transceiver Design**
  - Inter-symbol Interference
  - Time-Domain Equalization
  - Frequency-Domain Equalization
- **Conclusion**

Applications of Broadband Access

Residential Application	*Downstream rate (kb/s)*	*Upstream rate (kb/s)*	*Willing to pay*	*Demand Potential*
Database Access	384	9	High	Medium
On-line directory; yellow pages	384	9	Low	High
Video Phone	1,500	1,500	High	Medium
Home Shopping	1,500	64	Low	Medium
Video Games	1,500	1,500	Medium	Medium
Internet	3,000	384	High	Medium
Broadcast Video	6,000	0	Low	High
High definition TV	24,000	0	High	Medium

Business Application	*Downstream rate (kb/s)*	*Upstream rate (kb/s)*	*Willing to pay*	*Demand Potential*
On-line directory; yellow pages	384	9	Medium	High
Financial news	1,500	9	Medium	Low
Video phone	1,500	1,500	High	Low
Internet	3,000	384	High	High
Video conference	3,000	3,000	High	Low
Remote office	6,000	1,500	High	Medium
LAN interconnection	10,000	10,000	Medium	Medium
Supercomputing, CAD	45,000	45,000	High	Low

DSL Broadband Access

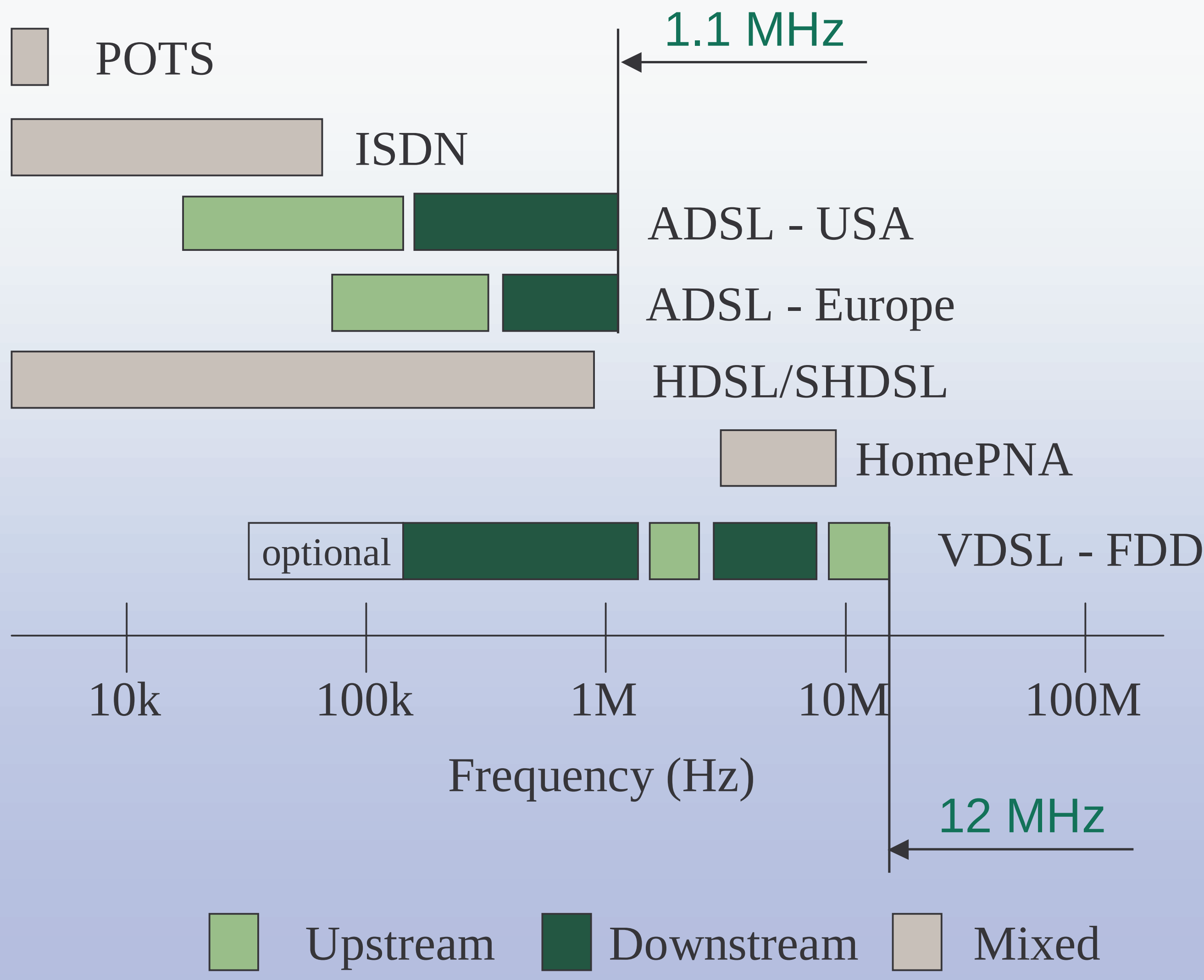


DSL Broadband Access Standards

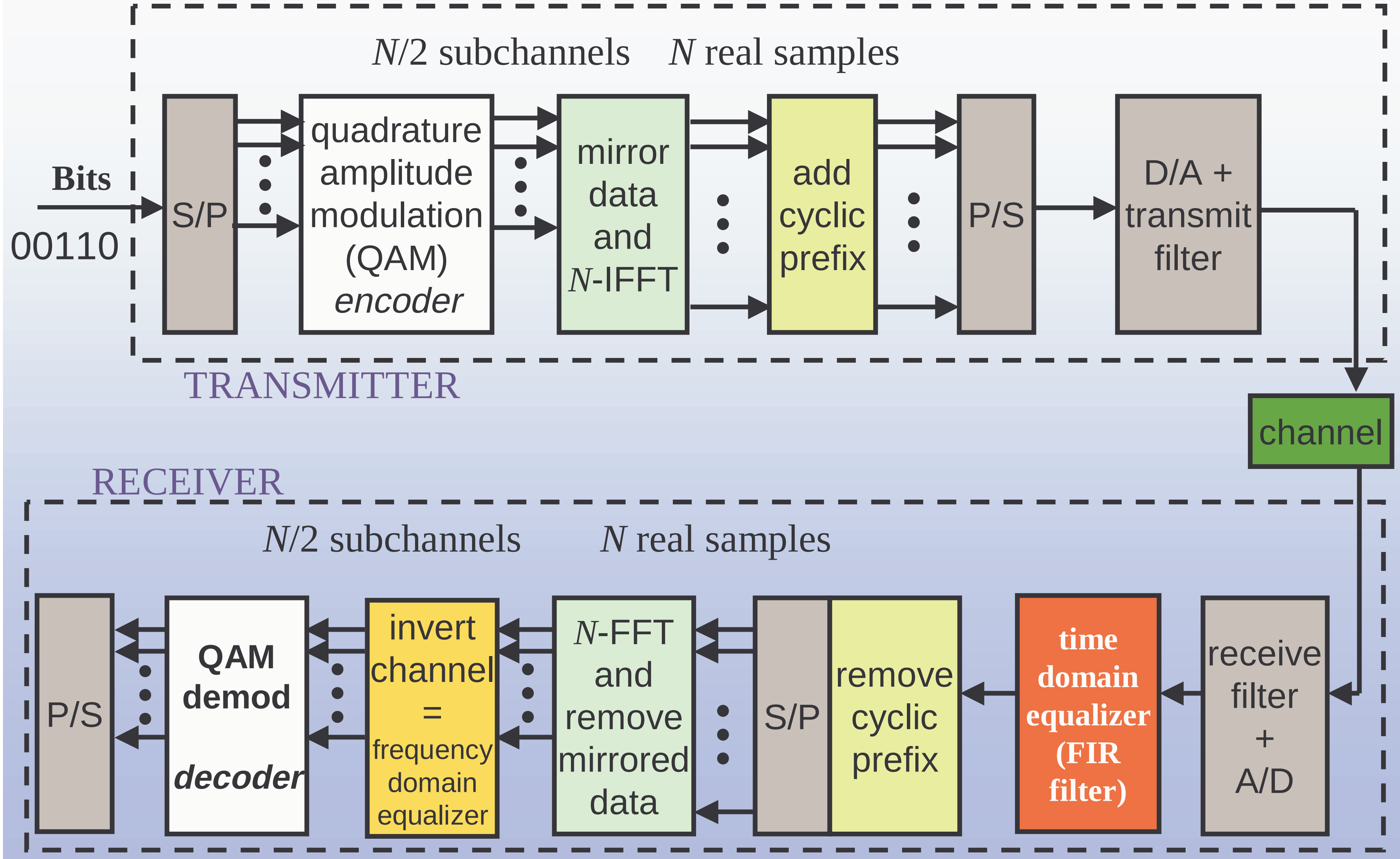
xDSL	*Meaning*	*Data Rate*	*Mode*	*Applications*
ISDN	Integrated Services Digital Network	144 kbps	Symmetric	Internet Access, Voice, Pair Gain (2 channels)
T1	T-Carrier One (requires two pairs)	1.544 Mbps	Symmetric	Business, Internet Service
HDSL	High-Speed Digital Subscriber Line (requires two pairs)	1.544 Mbps	Symmetric	Pair Gain (12 channels), Internet Access, T1/E1 replacement
SHDSL	Single Line HDSL	1.544 Mbps	Symmetric	Same as HDSL except pair gain is 24 channels
Splitterless ADSL	Splitterless Asymmetric DSL (*G.Lite*)	Up to 1.5 Mbps Up to 512 kbps	Downstream Upstream	Internet Access, Video Phone
Full-Rate ADSL	Asymmetric DSL (*G.DMT)*	Up to 10 Mbps Up to 1 Mbps	Downstream Upstream	Internet Access, Video Conferencing, Remote LAN Access
VDSL	Very High-Speed Digital Subscriber Line (proposed)	Up to 22 Mbps Up to 3 Mbps Up to 6 Mbps	Downstream Upstream Symmetric	Internet Access, Video-on-demand, ATM, Fiber to the Hood

Courtesy of Shawn McCaslin (Cicada Semiconductor, Austin, TX)

Spectral Compatibility of xDSL

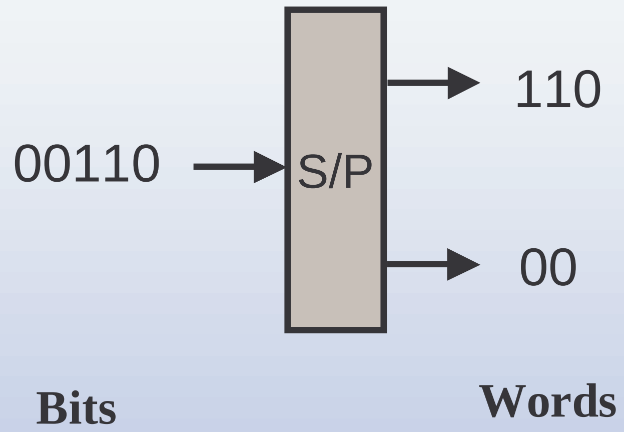


ADSL Modem

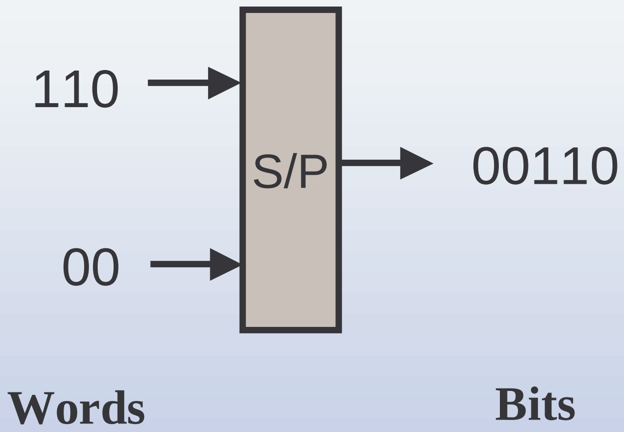

N/2 subchannels
N real samples
Bits
00110
S/P
quadrature amplitude modulation (QAM) encoder
mirror data and N-IFFT
add cyclic prefix
P/S
D/A + transmit filter
TRANSMITTER
channel
RECEIVER
N/2 subchannels
N real samples
P/S
QAM demod decoder
invert channel = frequency domain equalizer
N-FFT and remove mirrored data
S/P
remove cyclic prefix
time domain equalizer (FIR filter)
receive filter + A/D

Bit Manipulations

- **Serial-to-parallel converter**



- **Parallel-to-serial converter**



- **Example of one input bit stream and two output words**
- **Example of two input words and one output bit stream**

Amplitude Modulation by Cosine Function

- **Multiplication in time is convolution in Fourier domain**

$$y(t) = f(t)\cos(\omega_0 t)$$

$$Y(\omega) = \frac{1}{2\pi} F(\omega) * \pi\left(\delta(\omega+\omega_0) + \delta(\omega-\omega_0)\right)$$

- **Sifting property of the Dirac delta functional**

$$x(t) * \delta(t) = \int_{-\infty}^{\infty} \delta(\tau)\, x(t-\tau)\, d\tau = x(t)$$

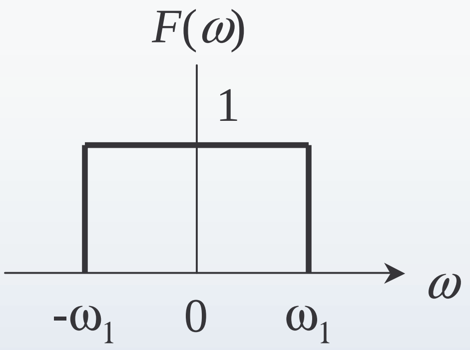
$$x(t) * \delta(t-t_0) = \int_{-\infty}^{\infty} \delta(\tau - t_0)\, x(t-\tau)\, d\tau = x(t-t_0)$$

- **Fourier transform property for modulation by a cosine**

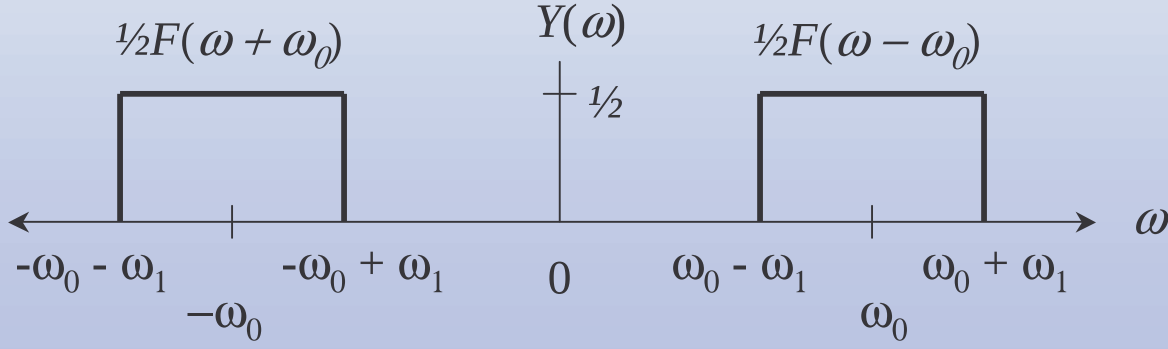
$$Y(\omega) = \frac{1}{2} F(\omega+\omega_0) + \frac{1}{2} F(\omega-\omega_0)$$

Amplitude Modulation by Cosine Function

- **Example:** $y(t) = f(t)\cos(\omega_0 t)$
  - $f(t)$ is an ideal lowpass signal
  - Assume $\omega_1 << \omega_0$
  - $Y(\omega)$ is real-valued if $F(\omega)$ is real-valued



$$Y(\omega) = \frac{1}{2} F(\omega + \omega_0) + \frac{1}{2} F(\omega - \omega_0)$$



- **Demodulation is modulation then lowpass filtering**
- **Similar derivation for modulation with** $\sin(\omega_0 t)$

Amplitude Modulation by Sine Function

- **Multiplication in time is convolution in Fourier domain**

$$y(t) = f(t)\sin(\omega_0 t)$$

$$Y(\omega) = \frac{1}{2\pi} F(\omega) * j\pi\left(\delta(\omega+\omega_0) - \delta(\omega-\omega_0)\right)$$

- **Sifting property of the Dirac delta functional**

$$x(t) * \delta(t) = \int_{-\infty}^{\infty} \delta(\tau)\, x(t-\tau)\, d\tau = x(t)$$

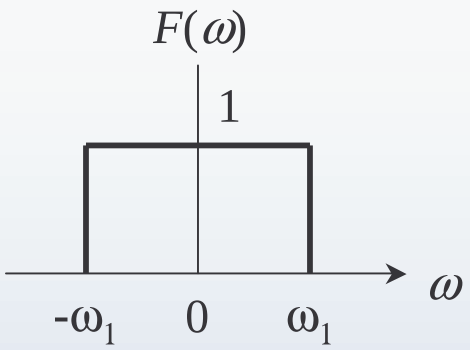
$$x(t) * \delta(t-t_0) = \int_{-\infty}^{\infty} \delta(\tau-t_0)\, x(t-\tau)\, d\tau = x(t-t_0)$$

- **Fourier transform property for modulation by a sine**

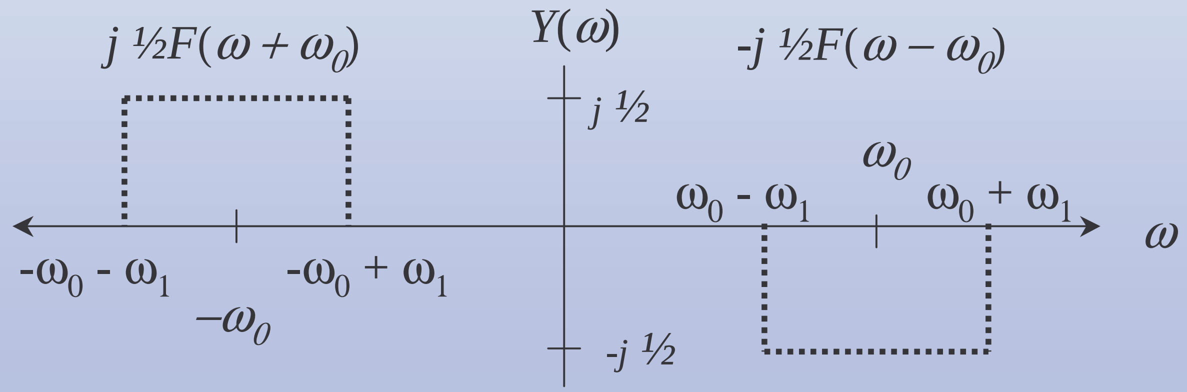
$$Y(\omega) = \frac{j}{2} F(\omega+\omega_0) - \frac{j}{2} F(\omega-\omega_0)$$

Amplitude Modulation by Sine Function

- **Example: $y(t) = f(t) \sin(\omega_0 t)$**
  - $f(t)$ is an ideal lowpass signal
  - Assume $\omega_1 << \omega_0$
  - $Y(\omega)$ is imaginary-valued if $F(\omega)$ is real-valued

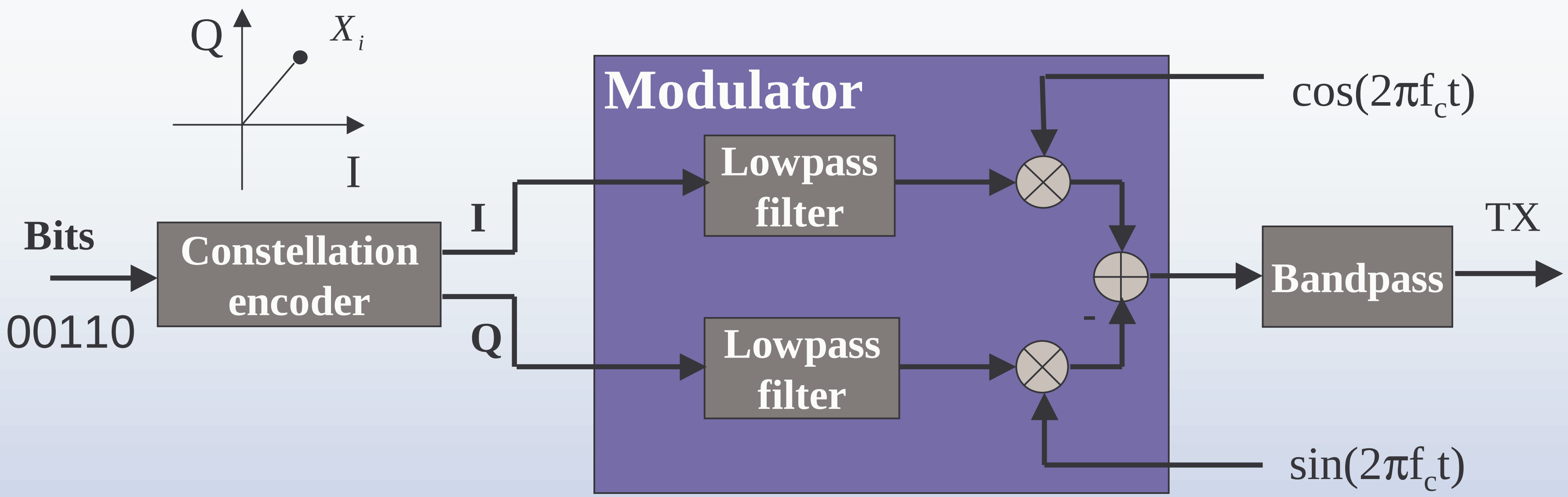


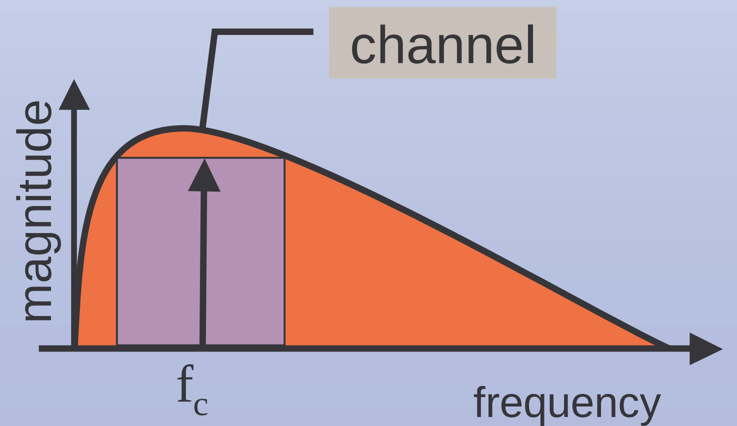
$$Y(\omega) = \frac{j}{2} F(\omega + \omega_0) - \frac{j}{2} F(\omega - \omega_0)$$



- **Demodulation is modulation then lowpass filtering**

Quadrature Amplitude Modulation (QAM)

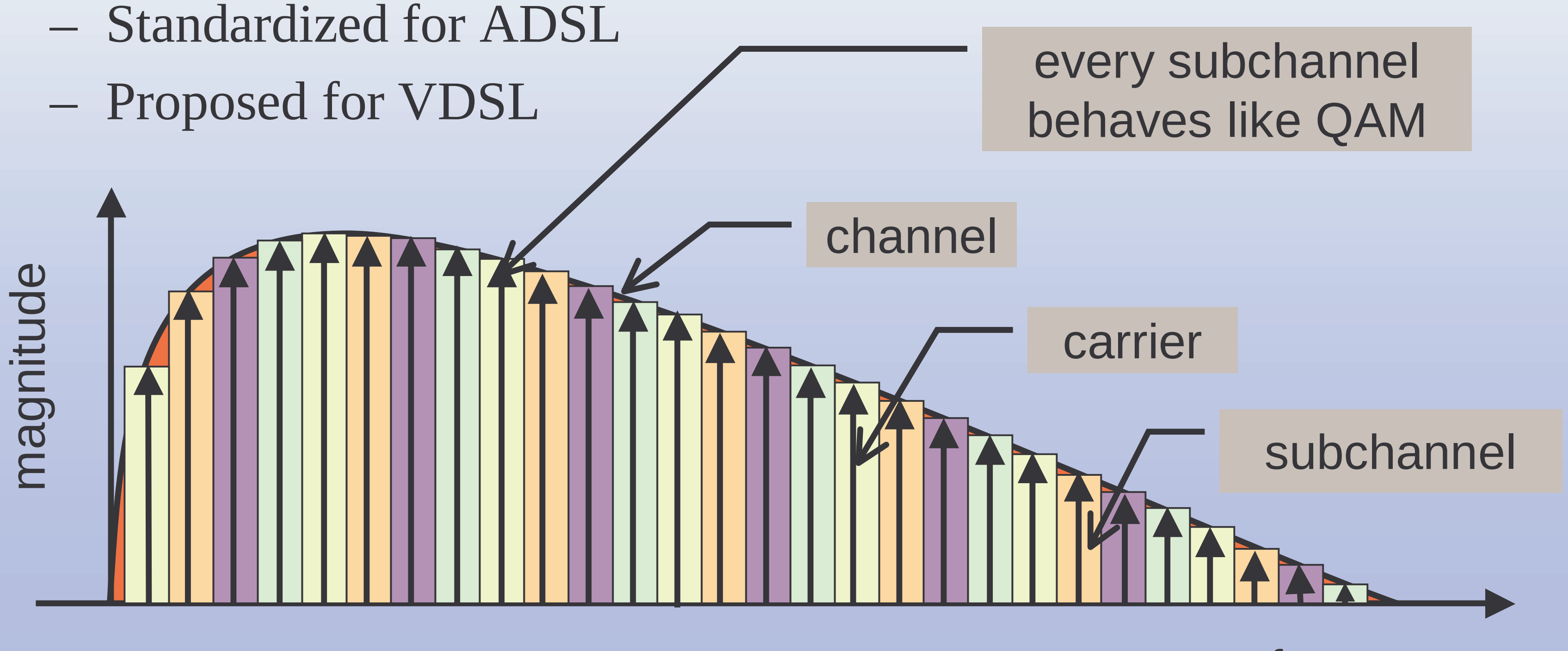




- One carrier
- Single signal, occupying the whole available bandwidth
- The symbol rate is the bandwidth of the signal being centered on carrier frequency

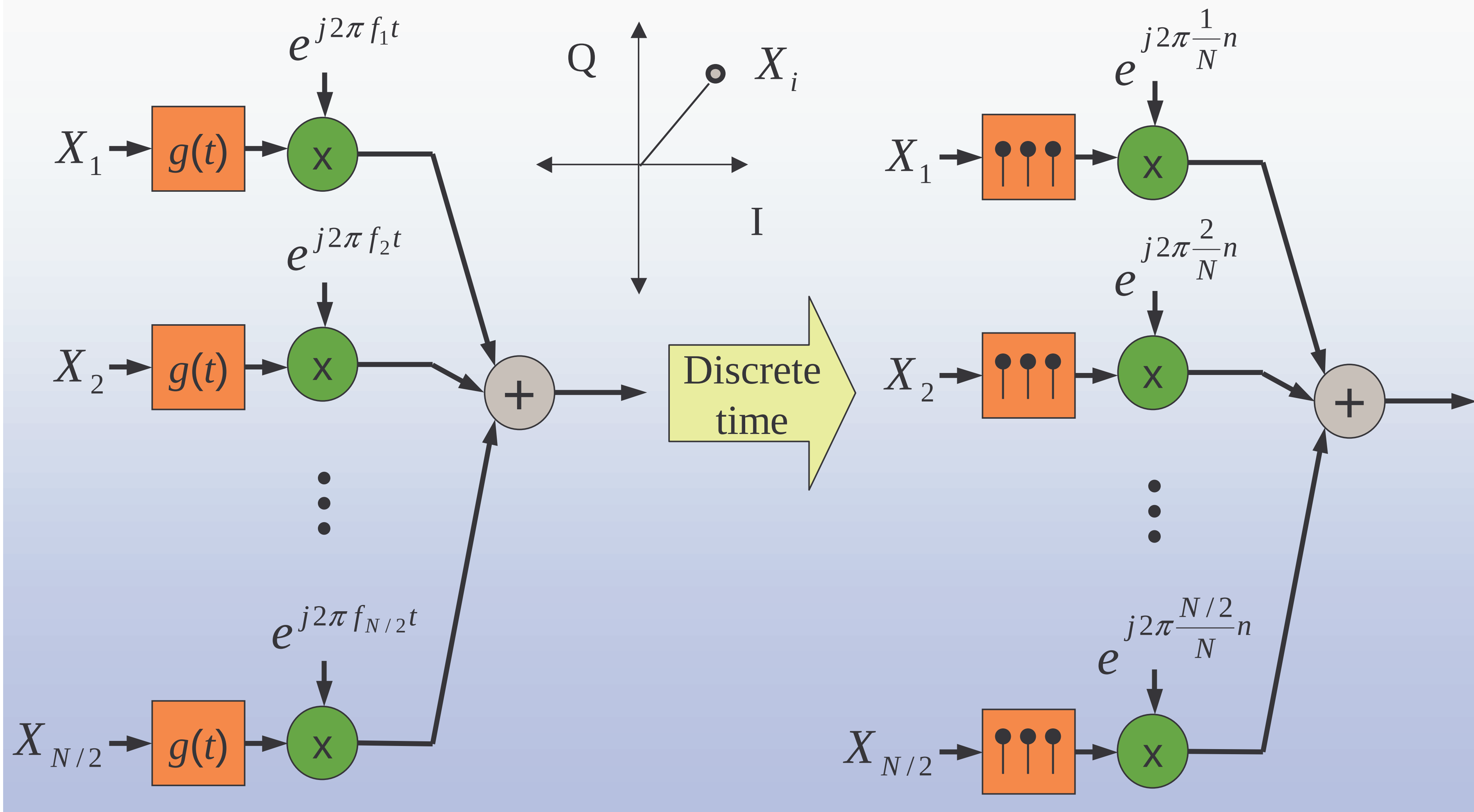
Multicarrier Modulation

- **Divide broadband channel into narrowband subchannels**
- **Discrete Multitone (DMT) modulation**
  - Based on fast Fourier transform (related to Fourier series)
  - Standardized for ADSL
  - Proposed for VDSL



Subchannels are 4.3 kHz wide in ADSL

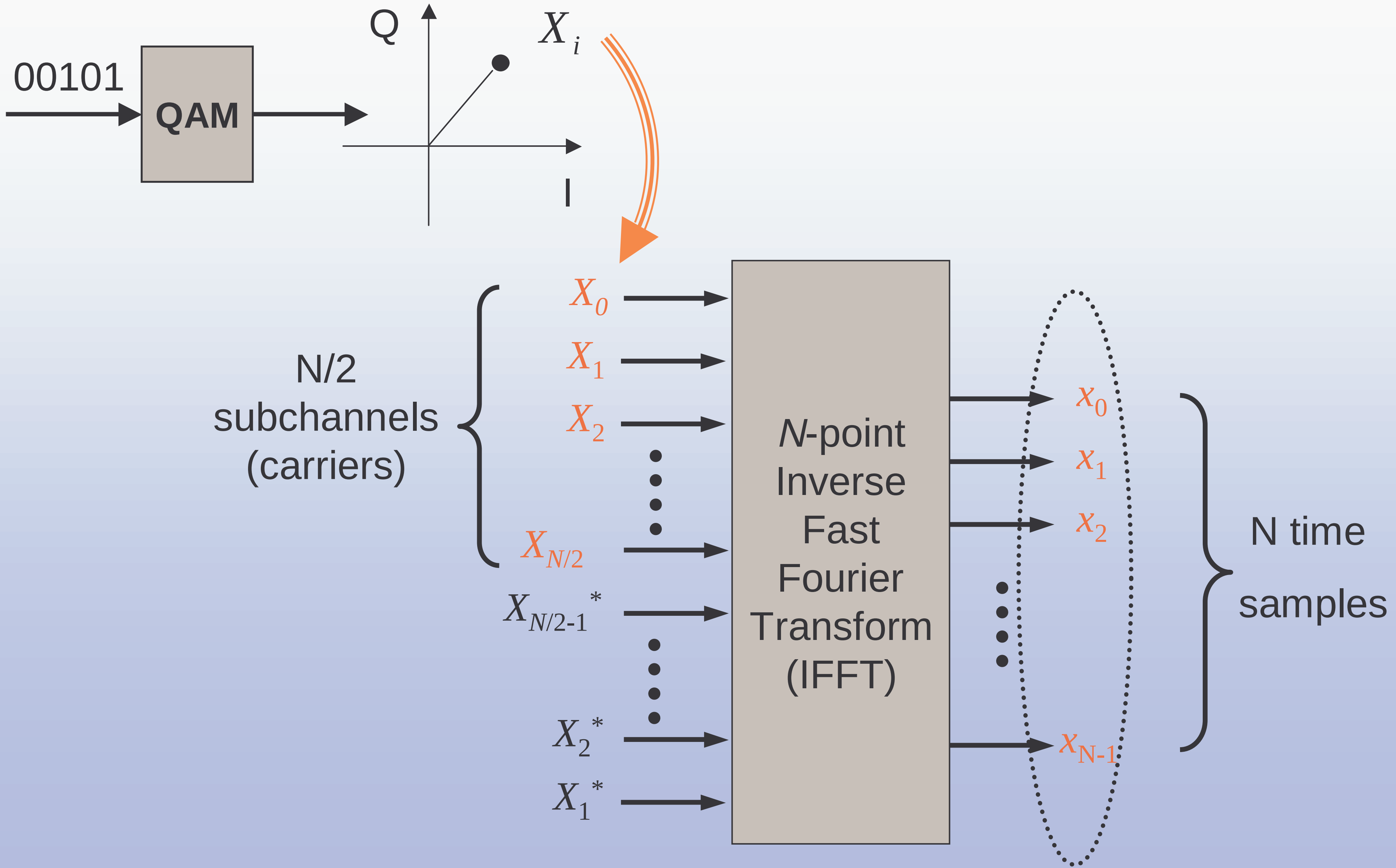
Multicarrier Modulation by Inverse FFT



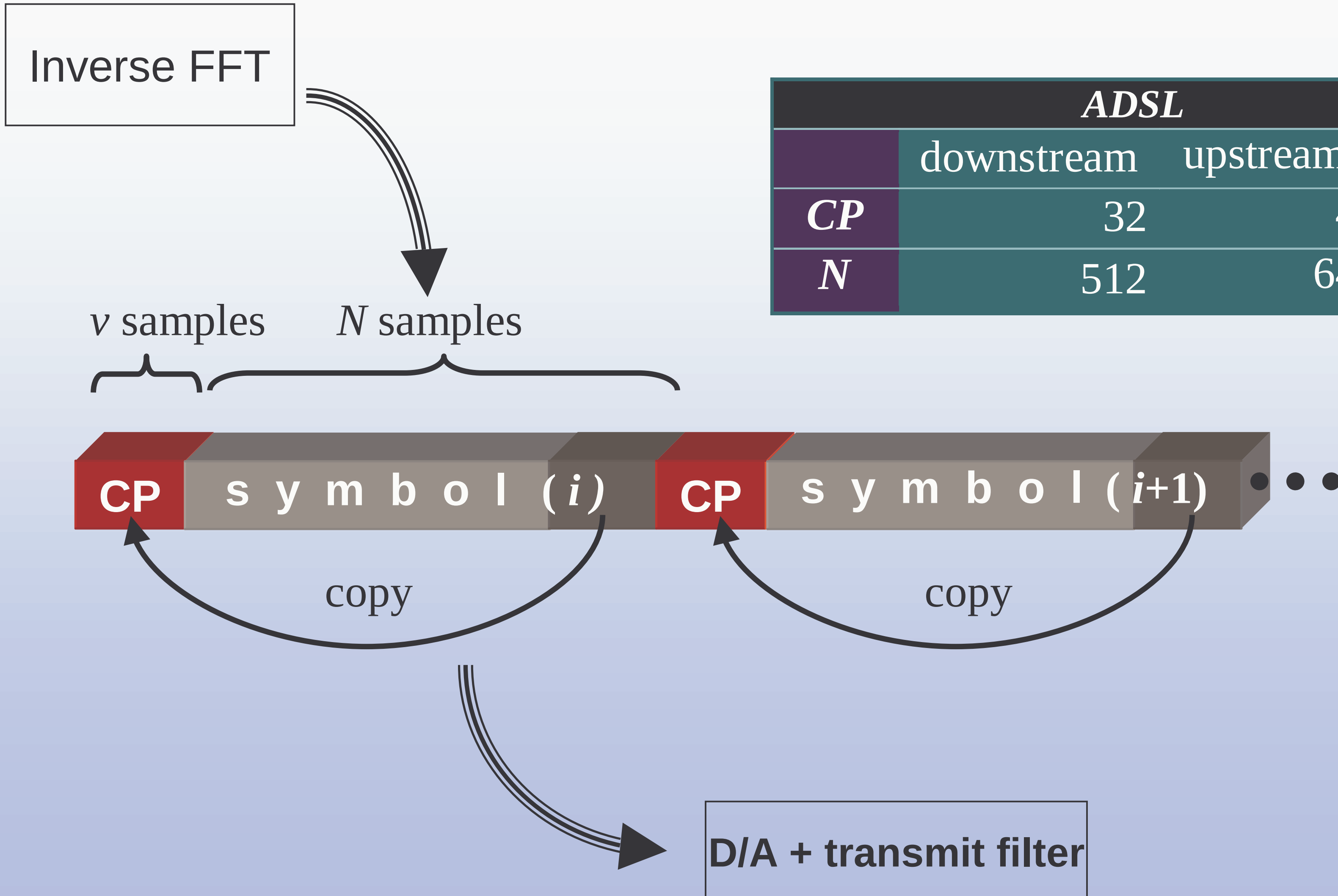
$g(t)$: **pulse shaping filter**

X_i : i^{th} symbol from encoder

Multicarrier Modulation in ADSL



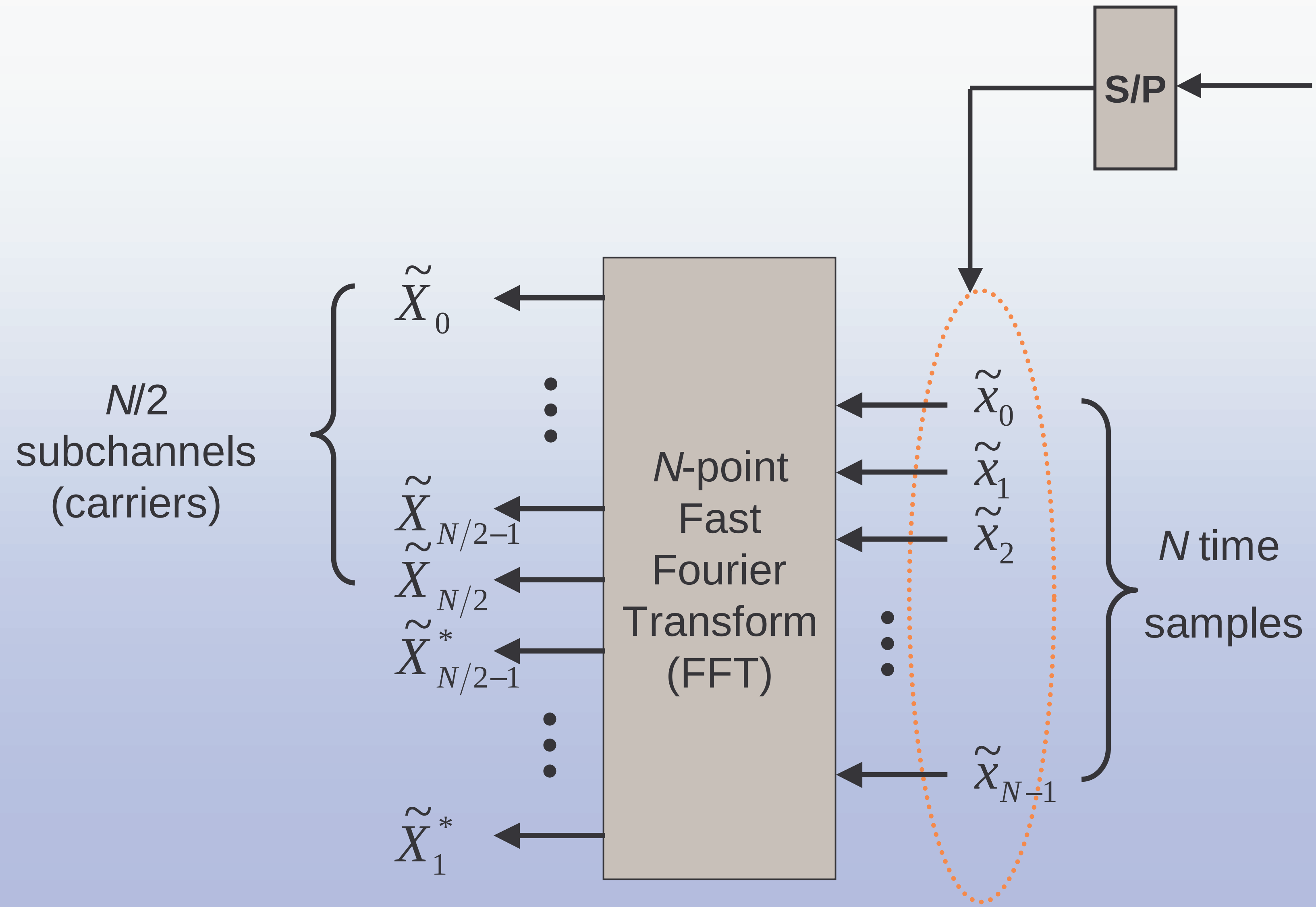
Multicarrier Modulation in ADSL



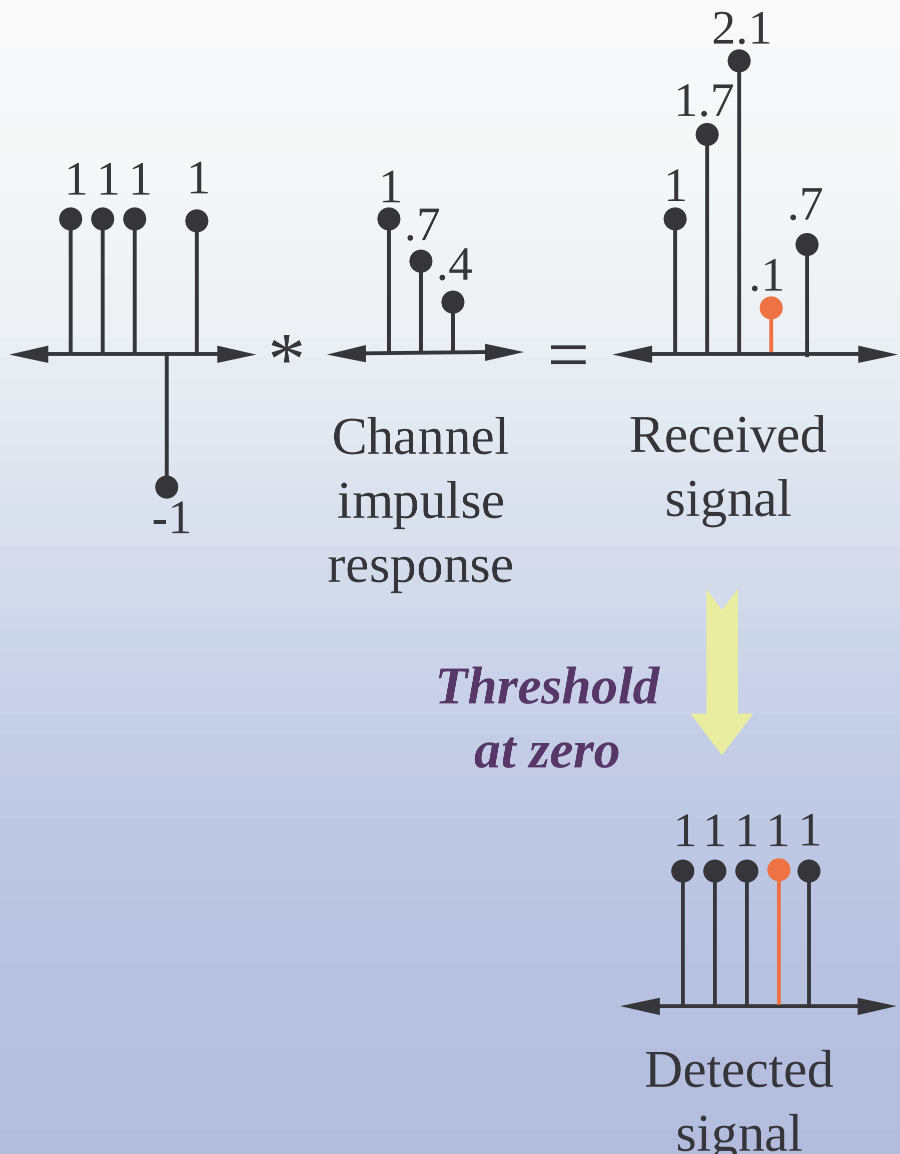
	ADSL	
	downstream	upstream
CP	32	4
N	512	64

CP: Cyclic Prefix

Multicarrier Demodulation in ADSL

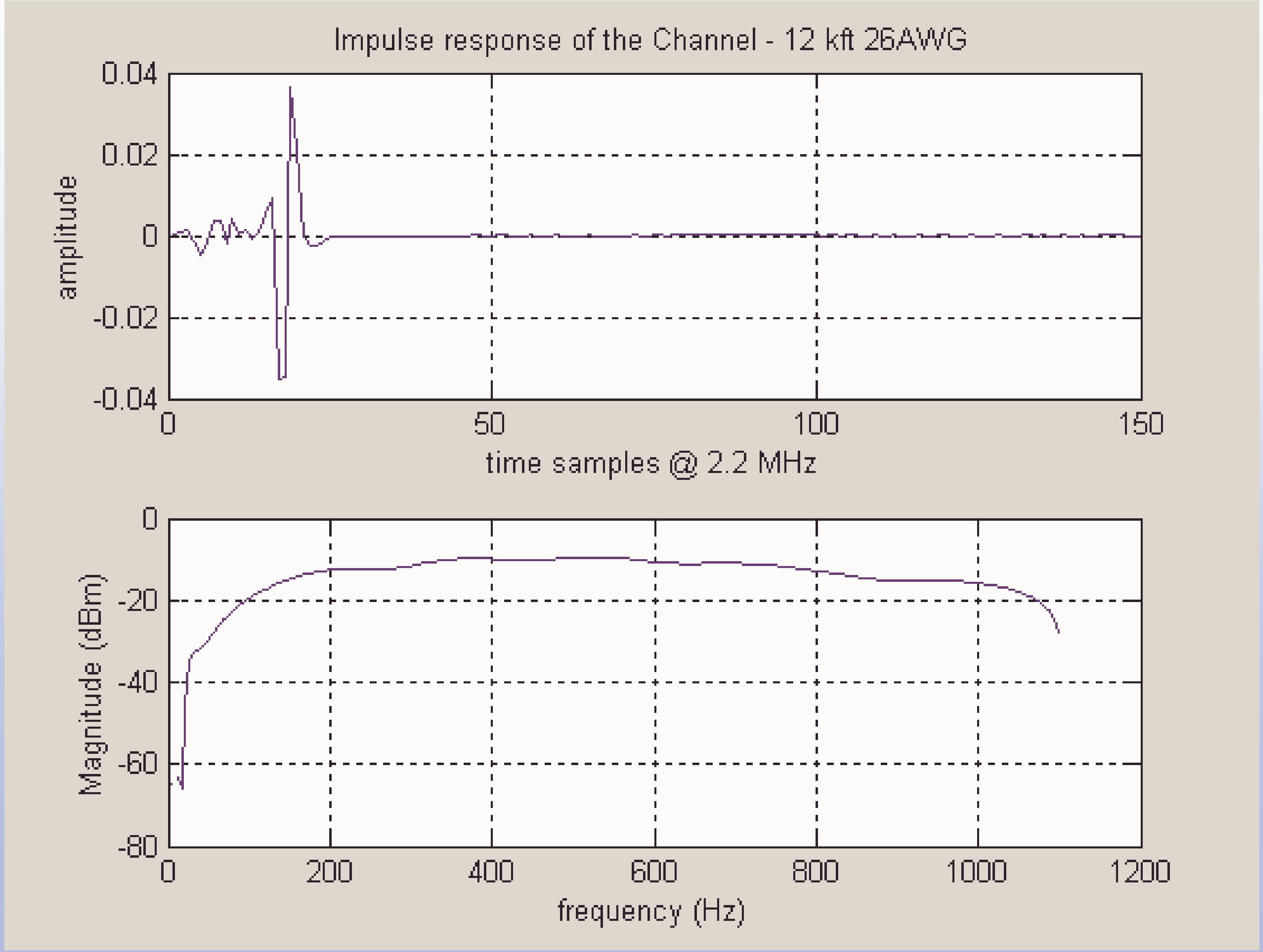


Inter-symbol Interference (ISI)

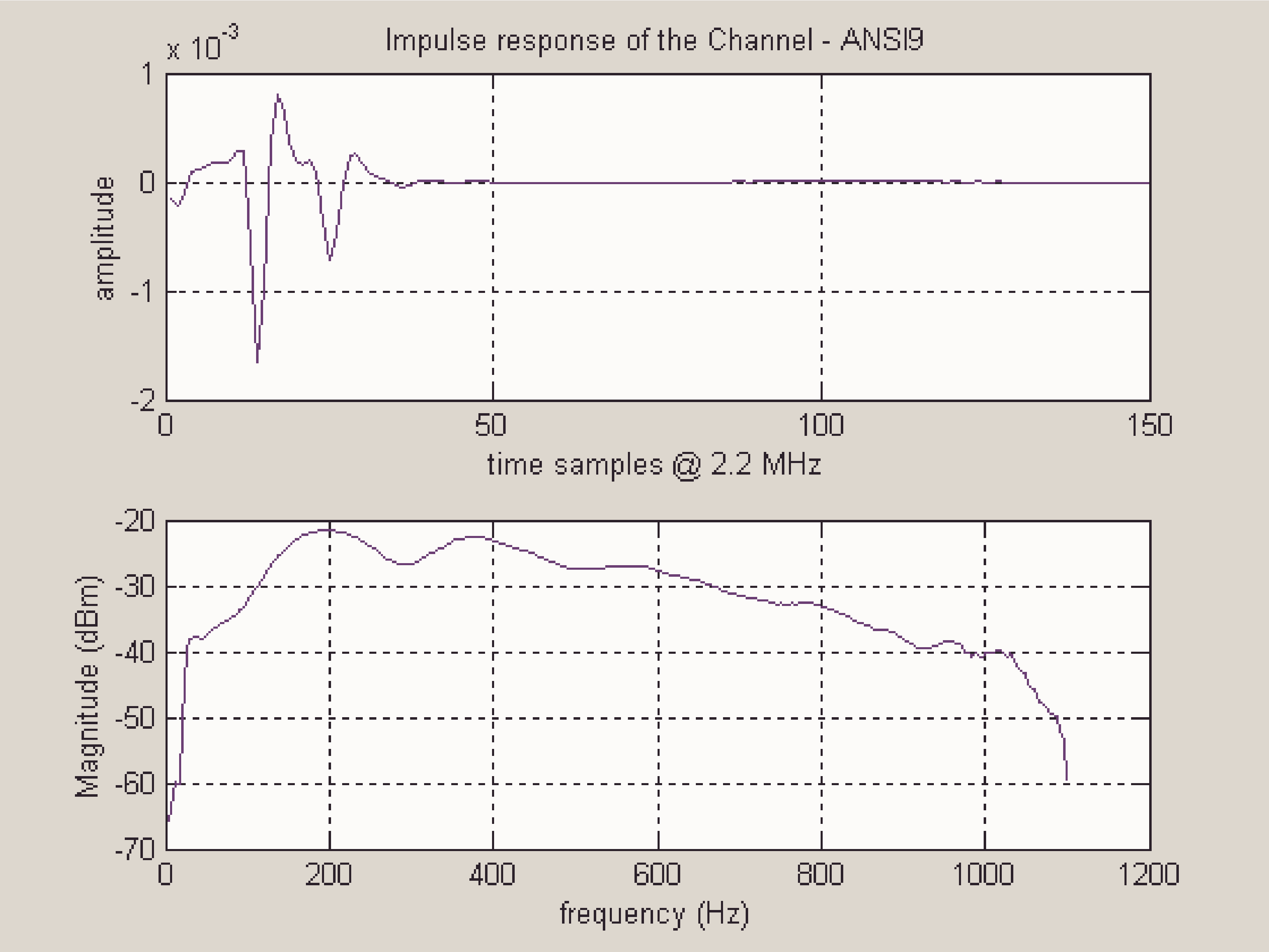


- **Ideal channel**
  - Impulse response is an impulse
  - Frequency response is flat
- **Non-ideal channel causes ISI**
  - Channel memory
  - Magnitude and phase variation
- **Received symbol is weighted sum of neighboring symbols**
  - Weights are determined by channel impulse response

Channel Impulse Response



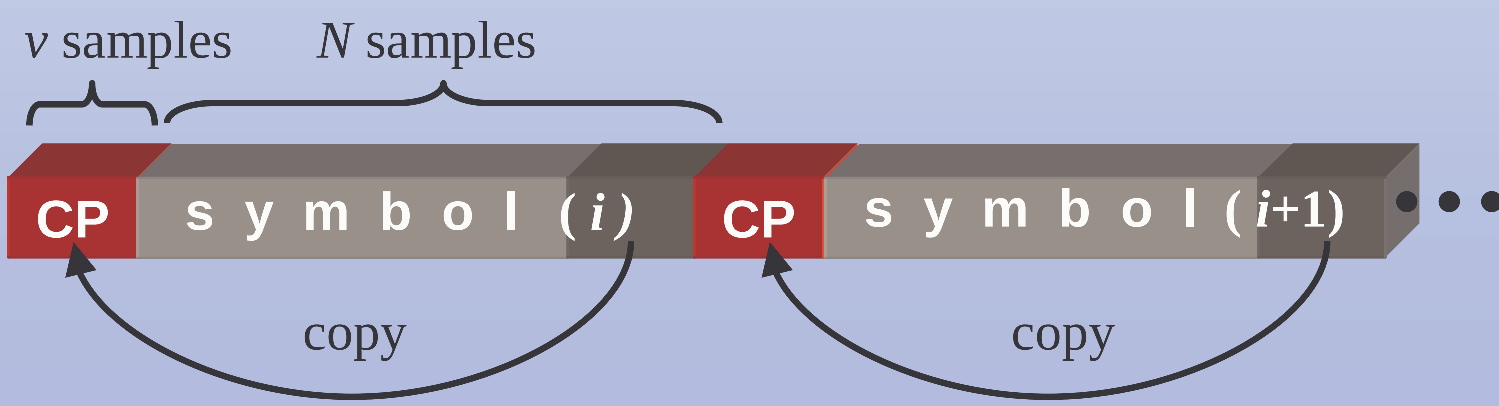
Channel Impulse Response



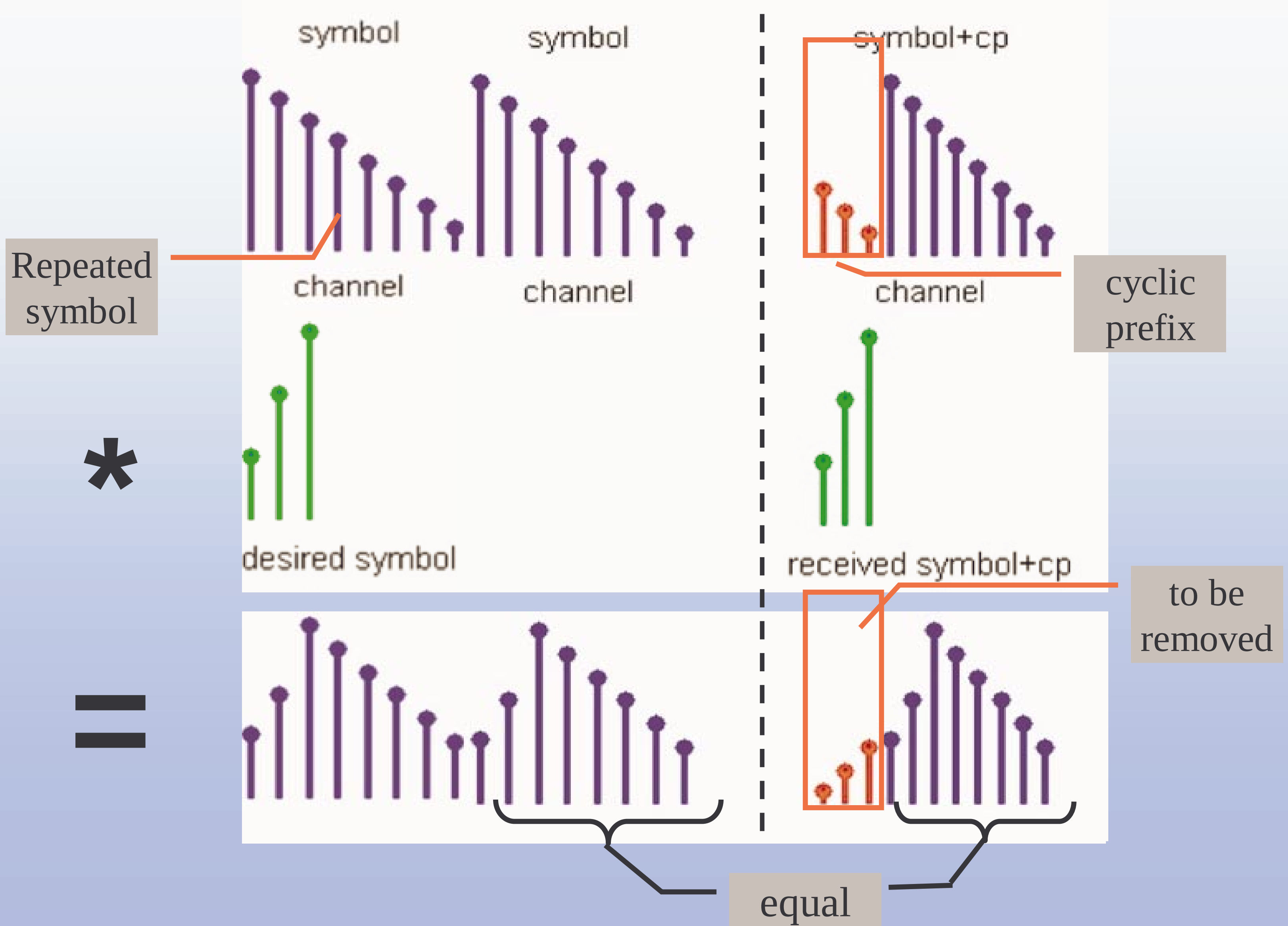
Cyclic Prefix Helps in Fighting ISI

- **Provide guard time between successive symbols**
  - No ISI if channel length is shorter than ν +1 samples
- **Choose guard time samples to be a copy of the beginning of the symbol – cyclic prefix**
  - Cyclic prefix converts linear convolution into circular convolution
  - Need circular convolution so that

    symbol ⊗ channel ⇔ FFT(symbol) x FFT(channel)
  - Then division by the FFT(channel) can undo channel distortion

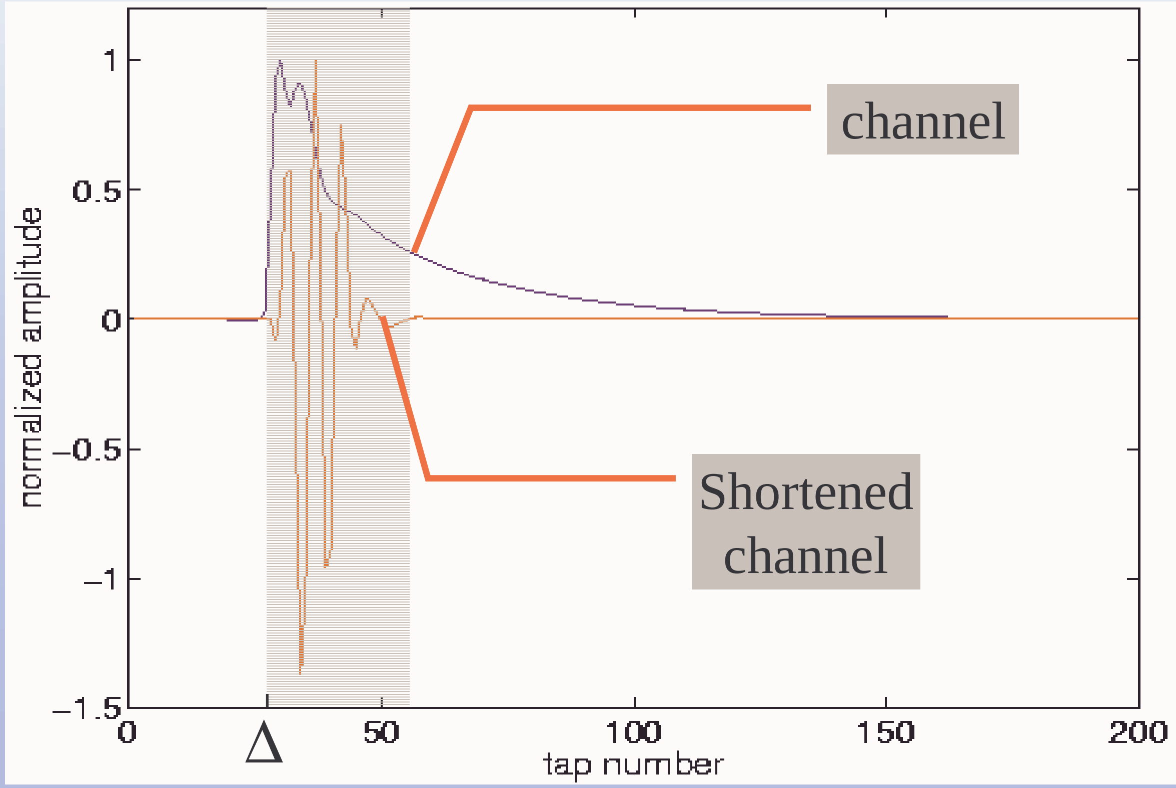


Cyclic Prefix Helps in Fighting ISI



Combat ISI with Time-Domain Equalizer

- **Channel length is usually longer than cyclic prefix**
- **Use finite impulse response (FIR) filter called a time-domain equalizer to shorten channel impulse response to be no longer than cyclic prefix length**

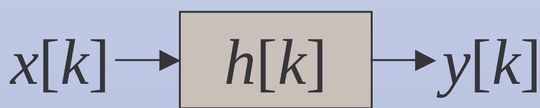


Convolution Review

- **Discrete-time convolution**

$$y[k] = \sum_{m=-\infty}^{\infty} h[m]\, x[k-m]$$

- **For every k, we compute a new summation**

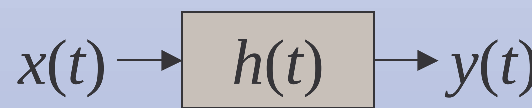


Represented by its impulse response

- **Continuous-time convolution**

$$y(t) = \int_{-\infty}^{\infty} h(\tau)\, x(t-\tau)\, d\tau$$

- **For every value of t, we compute a new integral**



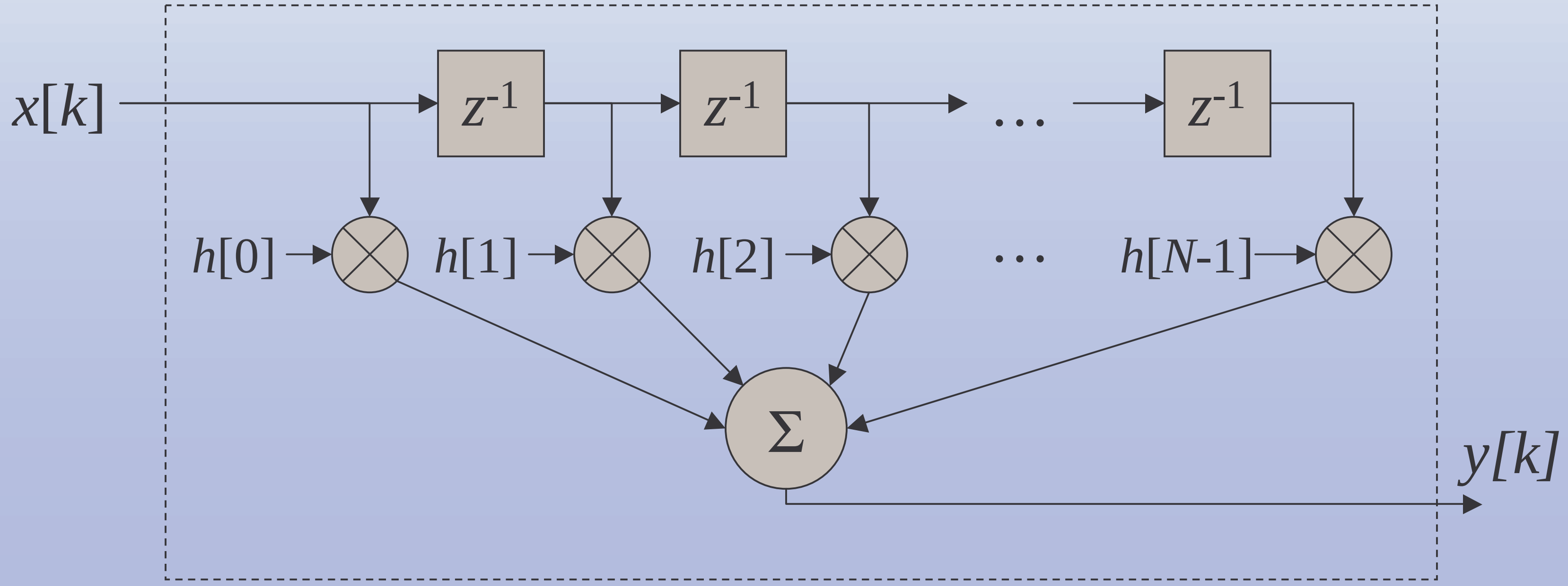
Represented by its impulse response

Finite Impulse Response (FIR) Filter

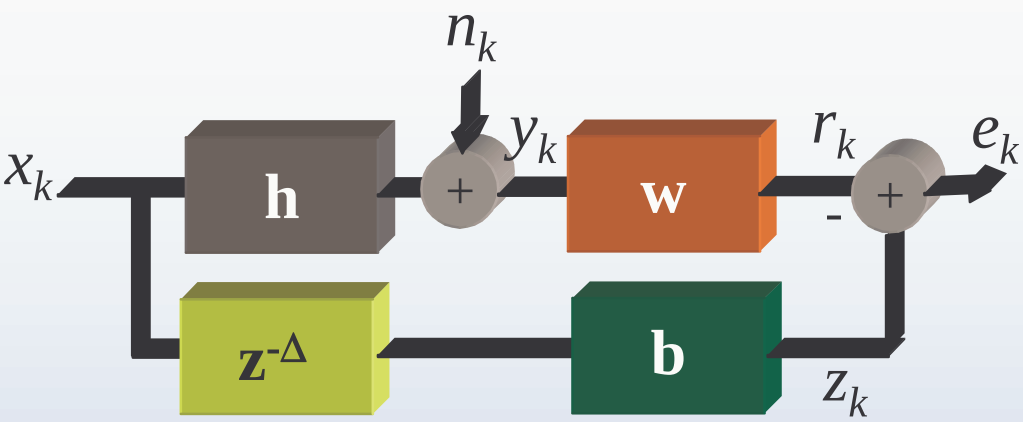
- **Assuming that *h*[*k*] is causal and has finite duration from *k* = 0, …, *N*-1**

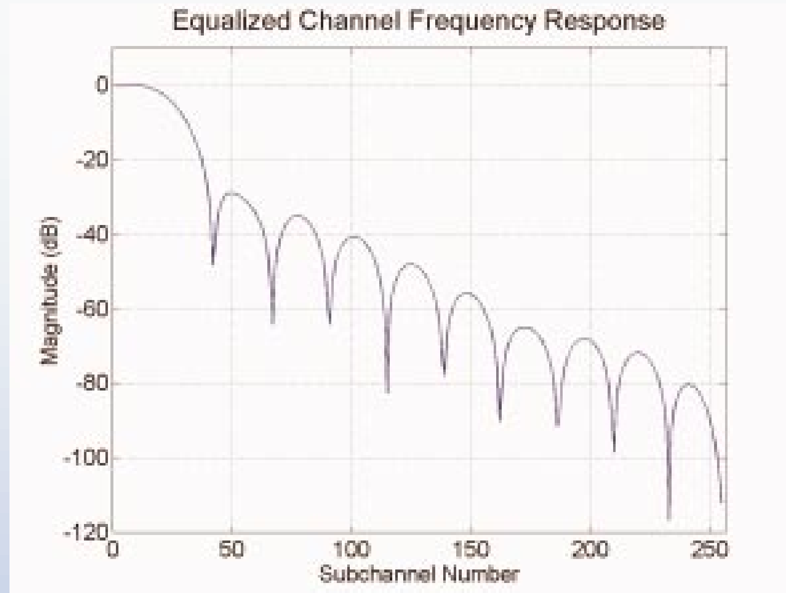
$$y[k] = \sum_{m=0}^{N-1} h[m]\, x[k-m]$$

- **Block diagram of an implementation (called a finite impulse response filter)**



Example Time-Domain Equalizer





- Minimize mean squared error

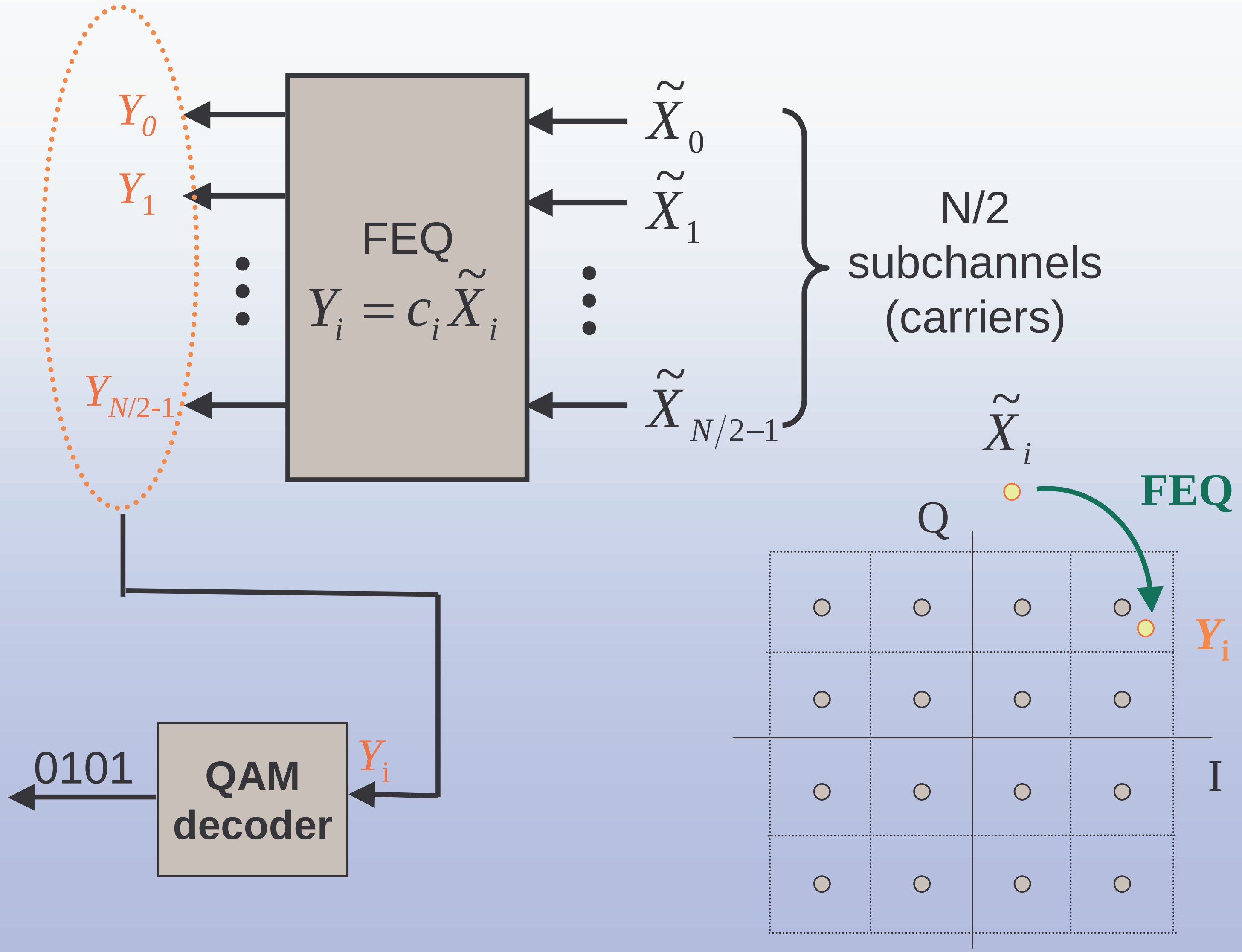
  $E\{e_k^2\}$ where $e_k = b_{k-\Delta} - h_k * w_k$

  – Chose length of b_k to shorten length of $h_k * w_k$
- Disadvantages
  – Does not consider *channel capacity*
  – Deep notches in equalizer frequency response

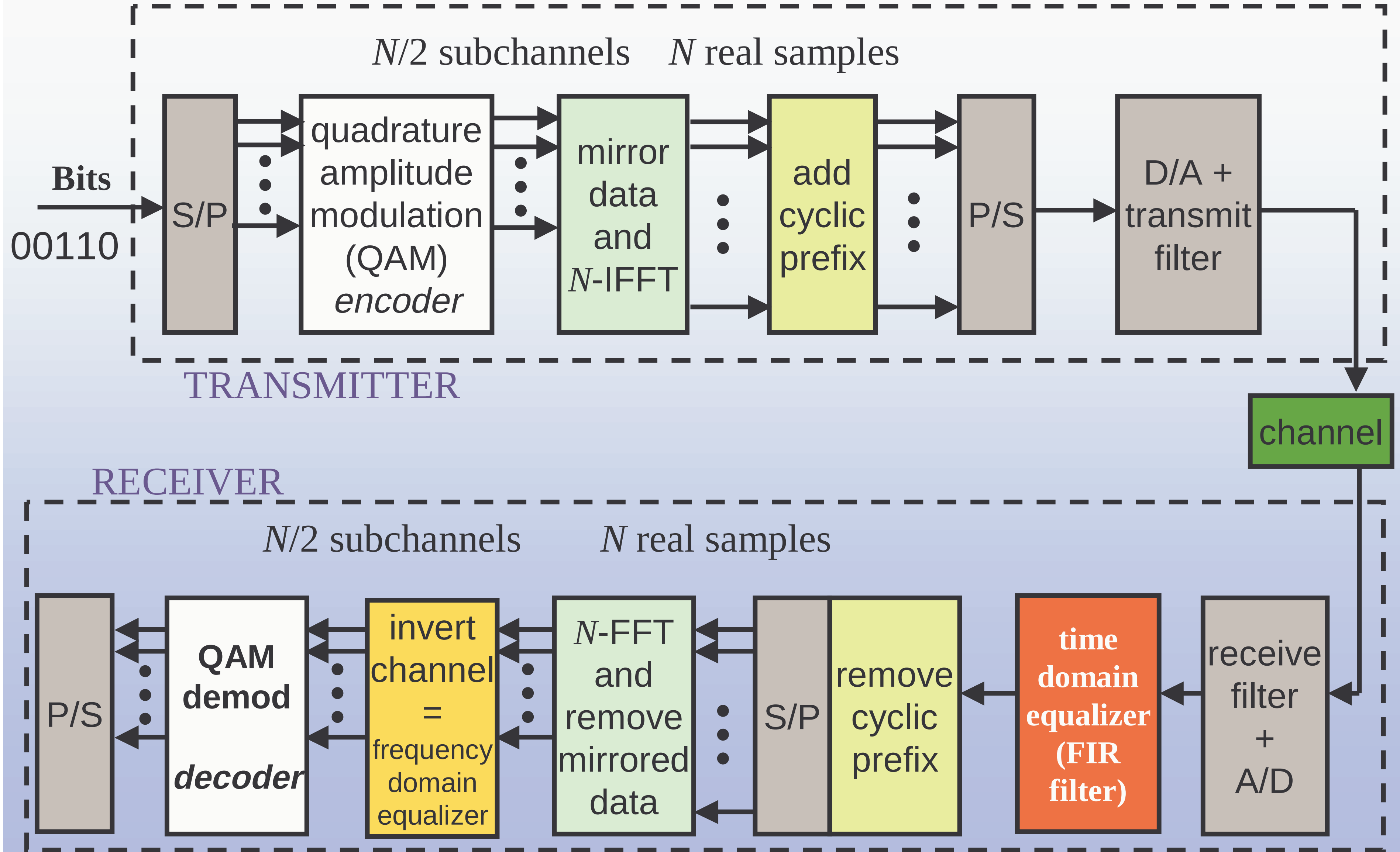
Frequency Domain Equalizer in ADSL

- **Problem: FFT coefficients (constellation points) have been distorted by the channel.**
- **Solution: Use Frequency-domain Equalizer (FEQ) to invert the channel.**
- **Implementation: N/2 single-tap filters with complex coefficients.**

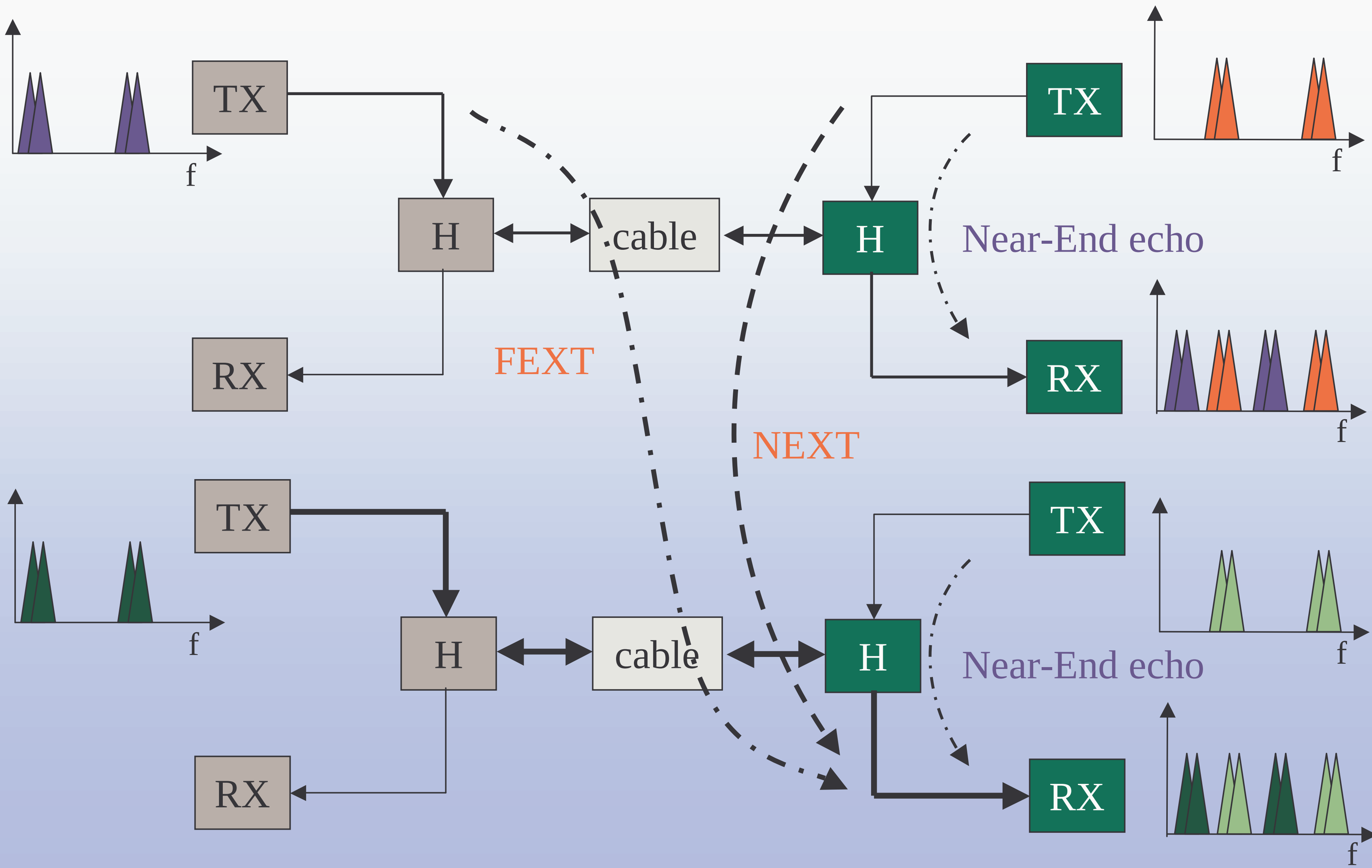
Frequency Domain Equalizer in ADSL



ADSL Modem


N/2 subchannels
N real samples
Bits
00110
S/P
quadrature amplitude modulation (QAM) encoder
mirror data and N-IFFT
add cyclic prefix
P/S
D/A + transmit filter
TRANSMITTER
channel
RECEIVER
N/2 subchannels
N real samples
P/S
QAM demod decoder
invert channel = frequency domain equalizer
N-FFT and remove mirrored data
S/P
remove cyclic prefix
time domain equalizer (FIR filter)
receive filter + A/D

Crosstalk and Near-End Echo



ADSL vs. FEXT, NEXT, Near-end Echo

- **ADSL with Freq. Division Multiplexing - FDM**
  - Near-End Echo filtered out
  - Self-NEXT (NEXT from another ADSL) mostly filtered out
  - FEXT and NEXT (from another type of DSL) are problems
- **ADSL with overlapped spectrum (Echo Cancelled)**
  - Near-End Echo Eliminated using an echo canceller
  - FEXT, NEXT and self-NEXT are a problem
  - Larger Spectrum available for downstream – higher data rate