Broadband access and the future of wireless communications
with a focus on OFDM as an enabling technology

Presentation to IEEE NJ Coast Communications/ Electromagnetic Compatibility/Vehicular Technology/ Antennas & Propagation Chapters

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November 9, 2006

Thank you for the invitation

I am honored by the invitation from the NJ Coast IEEE chapters, and pleased to be here with you.

This is a light technical overview, plus a closer look at OFDM. Most of the talk should be easy to follow for people from varied technical backgrounds.

I gave this talk last month at the Technical University of Munich in connection with receiving the Eduard Rhein Foundation Basic Research Prize for my early work on OFDM.

My background

I had the good fortune to observe and participate in the data communications and broadband access revolutions of the late 20th century.

AT&T Bell Labs 1968-1979
High-speed voiceband modems, early OFDM

American Express Company 1979-1984
Interactive cable services, smart cards

Bellcore (now Telcordia) 1985-1993
Broadband ISDN, multimedia applications

NEC USA Labs 1993-2001 (and continuing as a consultant)
DWDM optical communications, optical-wireless integration

and professionally,

active participation in the IEEE technical community over many years, including

1958 Joined IRE as a student member (now an IEEE Life Fellow)
1970s Developed IEEE Communications from a newsletter into a technical magazine.
1992 Co-founded the IEEE/ACM Transactions on Networking
1996-97 President IEEE Communications Society
(currently Chief Information Officer)
2002-2003 Member IEEE Board of Directors

I am now one of the "old guys" watching younger colleagues take the lead.

This talk ...

... offers views from my experience and describes varied approaches to broadband access communications and the techniques they share. I give special attention to OFDM (orthogonal frequency division multiplexing), an enabling technology in many systems, and suggest where I believe broadband wireless infrastructure is going.

Broadband services ...

... began long before the Internet.

- Television broadcasting
  Standards and early television broadcasts and receivers in the 1930s, deployments delayed until after WWII. Converting now to digital.

Philo Farnsworth

Telefunken television receiver, Germany, 1938

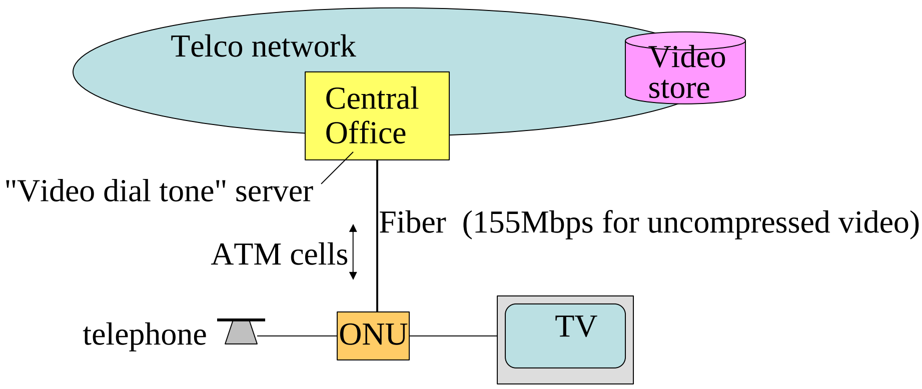
RCA demo television receiver, World's Fair, NYC, USA 1939

Ref: www.earlytelevision.org/prewar.html

- AT&T's Videophone (late 1960s)
  Almost a service, abandoned under pressure to improve regular telephone service in New York City.

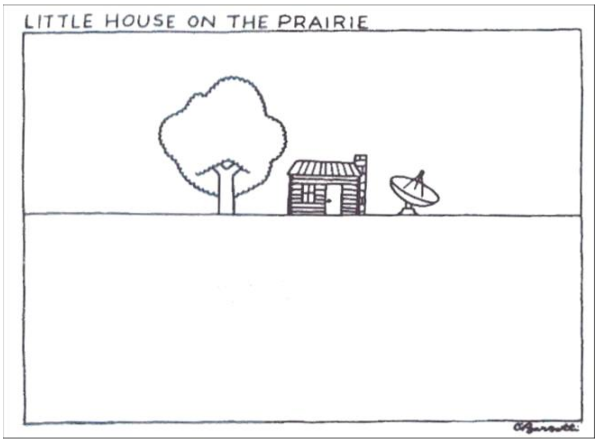
Videoconferencing
Very early experiments.
Commercial beginning in 1970s, partly in response to the oil boycotts and resulting increase in the cost of travel.

- Telco "video dialtone" (late 1980s-early1990s)
  BISDN (broadband integrated services network) services, particularly movies on demand.



Too expensive (about $2400/subscriber) to be deployed, and unrealistic aspirations of telcos to be content providers.

- Direct satellite broadcasting (early 1980s)
  Still a viable video programming service, plus two-way Internet access for rural subscribers.



Source: The New Yorker, 1983

The challenges for broadband access

-Coordinating incremental investment in access facilities with economic realities (advertising and revenue-generating applications). Providers are aiming for "triple play" (video entertainment, Internet access, telephony) in one system.

-Employing new techniques and technologies to make better and more cost-effective use of the channel available in each access system, and provide QoS* as needed for each service.

* QoS: Quality of Service (data rate, delay & error rate bounds, availability, ease of access, ...)

Broadband* access systems

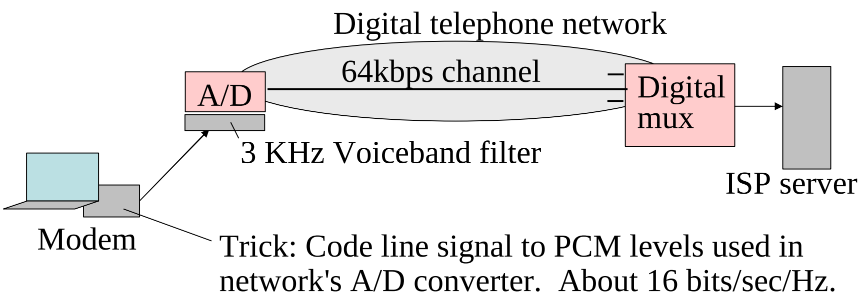
- Developed over time with different goals and capabilities.

- Never seem to disappear or be completely replaced – they evolve.

- Converging to a common tiered architecture, often with wireless users, and increasingly share techniques and technologies.

* I define broadband very loosely as any access rate significantly better than dialup modems (9600 bps) of the 1970s.

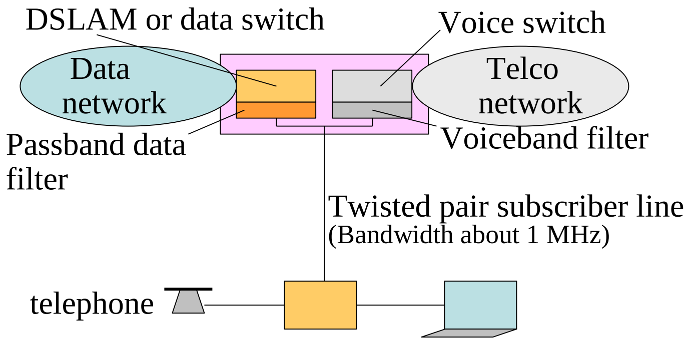
1. Faster dialup access through the telephone network.
   Realized, in 1990s, in V.90 series modems (64kbps max).



Still very useful in low-population-density areas.

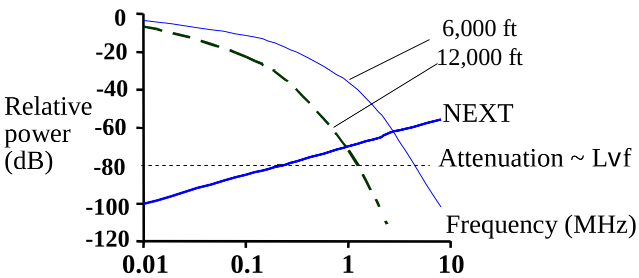
2. Twisted pair access line linked to a digital network rather than the telephone network.

Realized in ISDN and xDSL. Usually uses subscriber-installed modem. Advantageous use of existing lines.



DSLAM: Digital subscriber line access multiplexer

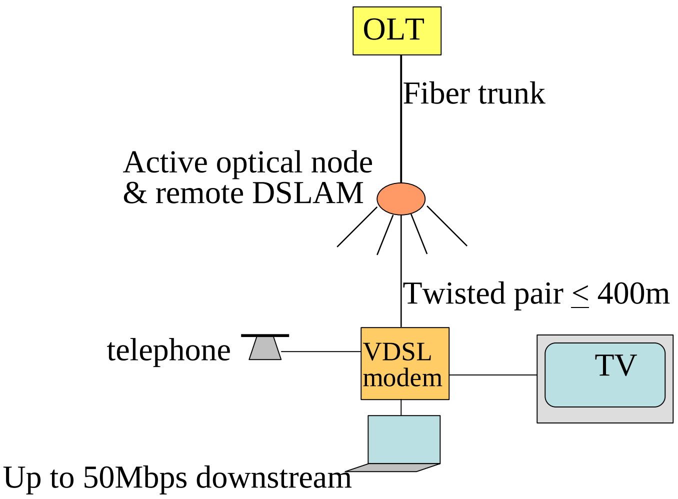
Problems: Development of ISDN too little-too late; ADSL performance suffers from crosstalk and distance from serving office. Range about 4km, capable of supporting only about 75% of U.S. residences.



Source: Paul Henry, AT&T Labs

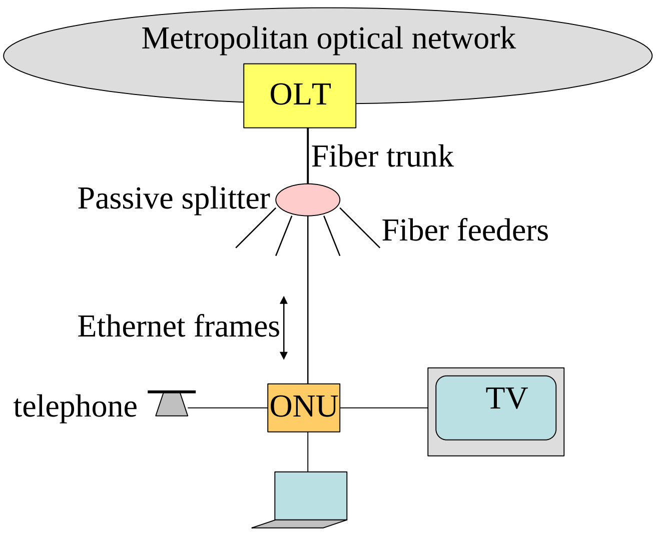
Optimistic future: VDSL (next slide)

VDSL (very high speed digital subscriber line)

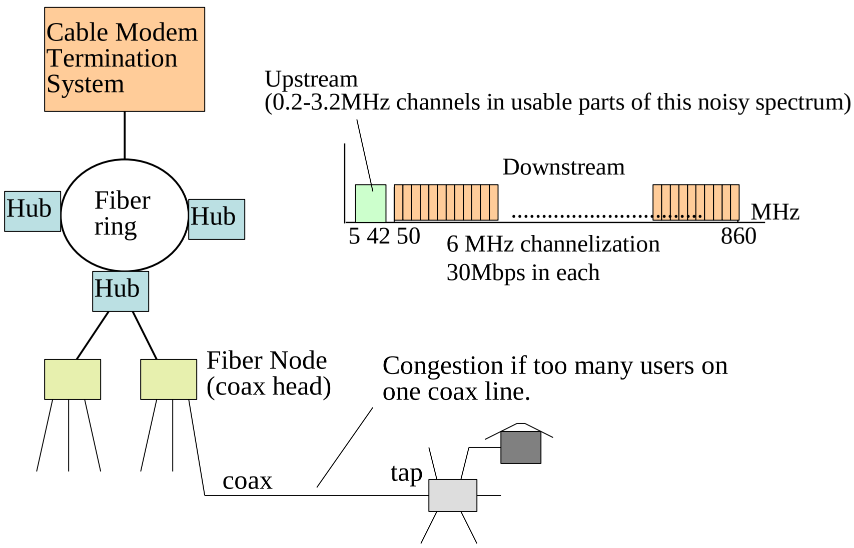


3. Optical fiber all the way to the subscribers

Originally ATM-based BISDN, but illustrated here with modern EPON (Ethernet passive optical network)



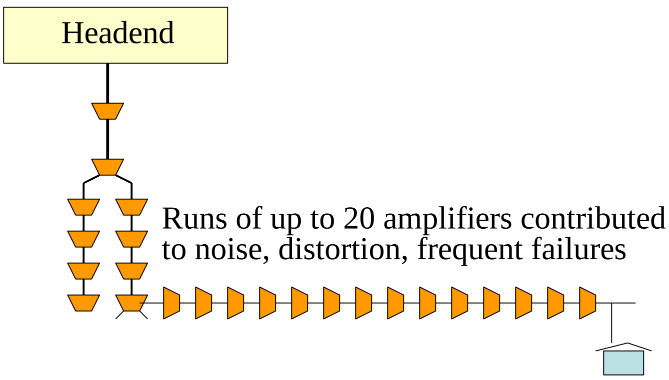
4. HFC (hybrid fiber/coax)



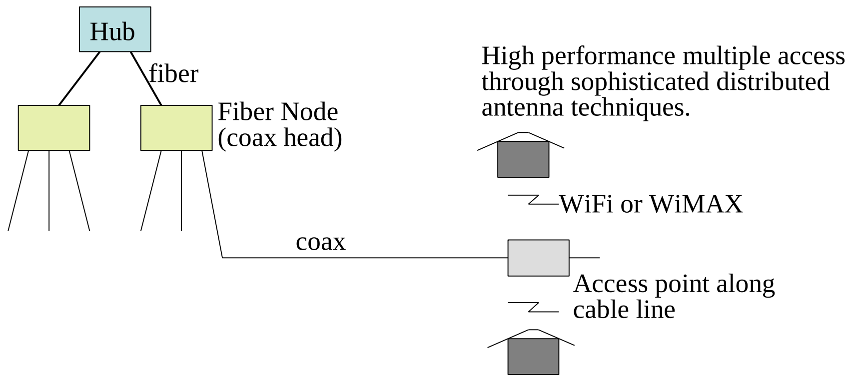
DOCSIS: Data-Over-Cable Service Interface Specifications: Radio Frequency Interface Specification SP-RFIv1.1-I06-001215, Cable Laboratories, December 15, 2000

Aside: Why are there more cable data than ADSL subscribers in the U.S.?

-Cable systems 15-20 years ago began major upgrades to HFC to reduce maintenance costs and improve transmission performance, *before* digital services came along. They were, almost by accident, better prepared for digital services that can reach almost all CATV subscribers.



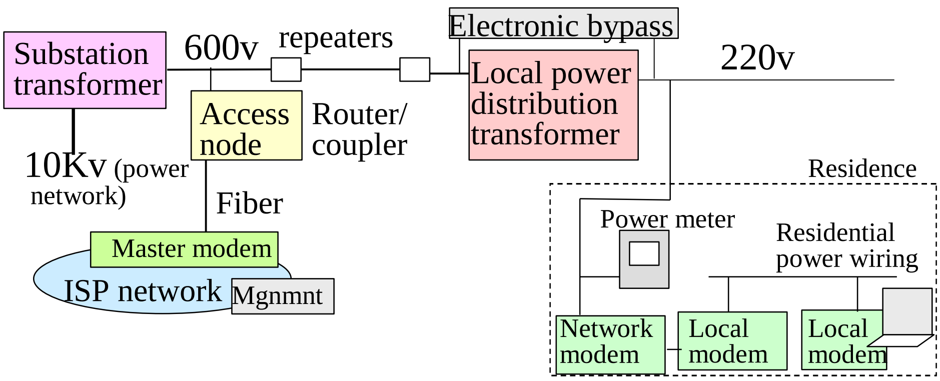
Cable data remains a strong competitor to ADSL.
May lose ground to VDSL or optical/wireless competition, but it can also implement an optical/wireless version.



Ref: S. Weinstein & J. Lechleider, "Multi-user wireless access to a digital cable system" Proc. IEEE Wireless Commun. & Networking Conf., March, 2004.

5. BoPL (broadband over power line)

Promising, but has problems of interference to other spectrum users (amateur radio operators in particular) and challenge in bypassing transformers.



IEEE P1901 (sponsored by Comsoc), Draft Standard for Broadband Over Power Line Networks: Medium Access Control and Physical Layer Specifications

6. Broadband IP*/optical/wireless

IP/Optical/ cellular mobile (3G/4G)
IP/Optical/WiMAX
IP/Optical/WiMAX/WiFi or Optical/WiFi
IP/Optical/UWB

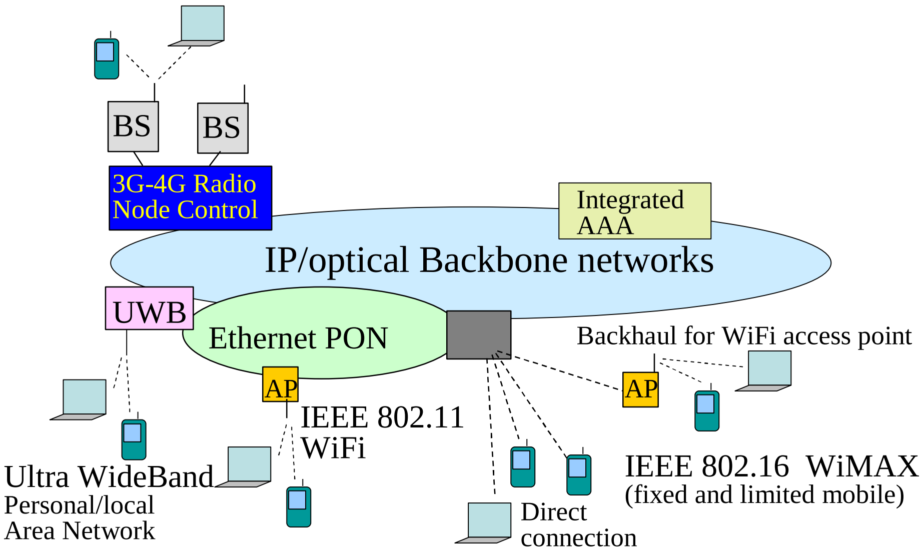
A common optical/wireless architecture.

This is the direction wireless seems to be going.

*IP: Internet Protocol. Watch out – the U.S. National Science Foundation is funding studies of a replacement of the IP protocol stack.

4G (fourth generation) cellular mobile may be the integration of diverse hybrid IP/optical/wireless environments, rather than a new cellular mobile system.

Optical/wireless integration in the access network



AAA: Authorization, access, accounting

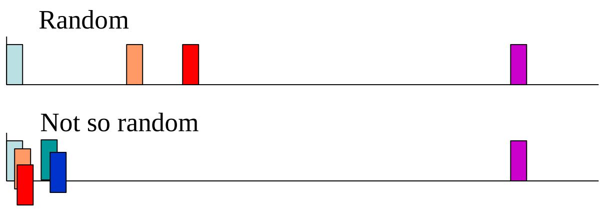
Enabling techniques and technologies

Key communication techniques and technologies support better use of spectrum in several different access systems and encourage hybrid systems.

An example

Exponential backoff contention resolution

MAC-level multiple access technique found in Ethernet, cable data systems, WiFi.
Distributed access control still being refined for fair contention resolution, QoS preferences, and good performance when job (capacity request) arrivals are not random.

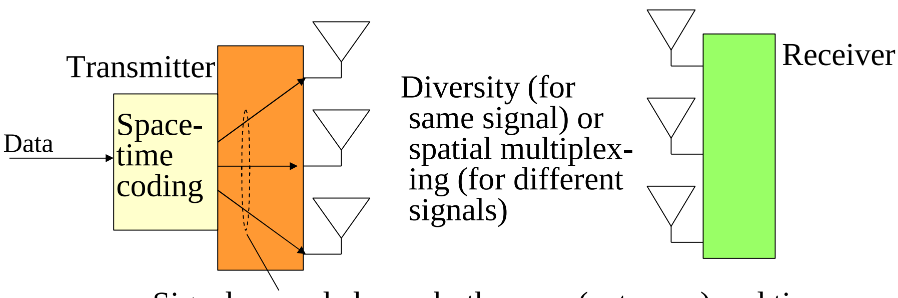


Solutions are useful for both computing and communication systems.

Another example:

MIMO (multiple in-multiple out)

Physical-level technique for cellular mobile and other wireless systems.
Multi-antenna wireless technology supporting large improvements in capacity, diversity protection, or a combination of both.



Signals encoded over both space (antennas) and time
Potential spectral efficiency of tens of bits/sec/Hz

Ref: Horst Bessai, MIMO Signals and Systems, Springer, 2005.

Another example:

OFDM (orthogonal frequency division multiplexing)

Physical level modulation system implemented in ADSL, WiFi, WiMAX, DAB, DVB, BoPL, UWB and (probably) 4G cellular systems.

In the competition between single carrier systems with full-channel equalization and OFDM systems with (very simple) subband equalization, OFDM appears to be winning with more flexibility* and lower implementation cost.

Topic of the rest of this lecture.

* Such as frequency-selective power/data rate allocation.

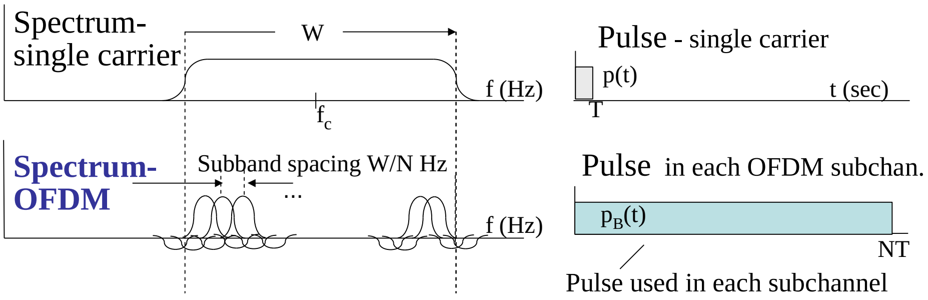
OFDM (Orthogonal Frequency Division Multiplexing)

What is it? A data signaling format in which data are transmitted in many narrow frequency subbands (multiple subcarriers) rather than in one relatively large band (single carrier).

The spectra of the subband signals overlap but there is (ideally) no interference among them.

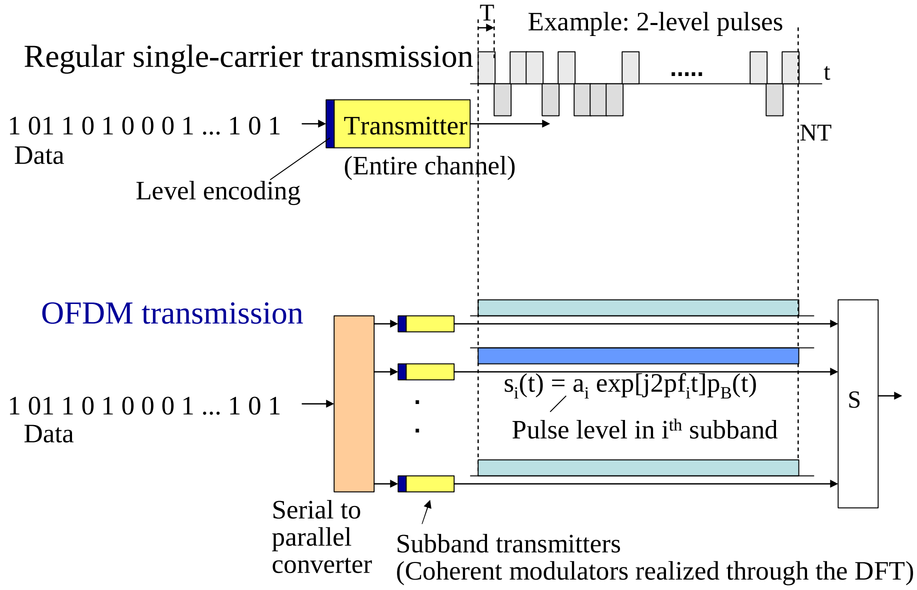
Some of the main ideas have been around for a long time.

Comparison of single carrier spectrum and pulses with those of an OFDM system



Note: For simplicity, I show here only one of a string of consecutive pulses for each system.

Conceptual transmitter comparison



OFDM signals are generated today using the computationally efficient Fast Fourier Transform to calculate a Discrete Fourier Transform of a block of input data

Definition:

Forward discrete Fourier transform (N point)

$$y_i = (1/N) \sum_{n=0}^{N-1} x_n \exp\{-j2\pi in/N\}, \quad i=0,...,N-1$$

Inverse discrete Fourier transform (N point)

$$x_n = \sum_{i=0}^{N-1} y_i \exp\{j2\pi in/N\}, \quad n = 0,...,N-1$$

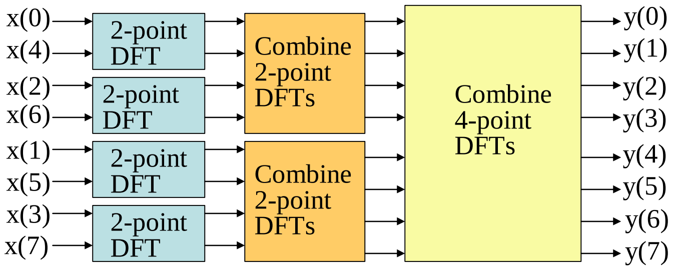
Fast Fourier Transform (FFT)

- A way of organizing computation of the DFT that greatly reduces the number of multiplications and additions for large N.

- Usually implemented by the Cooley-Tukey algorithm (1965). May actually go back to Karl Friedrich Gauss (around 1805).

- It exploits periodicity and symmetry properties of exponentials.

- It uses successive decimations. For N=8 it looks like:



Why the "orthogonal" in orthogonal frequency division multiplexing?

Because even though subband spectra overlap, the subband signals are orthogonal to each other over the duration of an OFDM pulse.

$$\int_0^{NT} s_i(t)\, s_j(t)\, dt = 0, \quad i \neq j$$

NT (OFDM pulse duration)

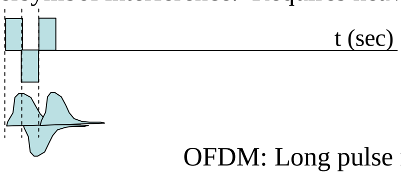
If measures are taken to avoid intersymbol (interpulse) interference, data can be correctly recovered in the receiver.

What OFDM is good for:

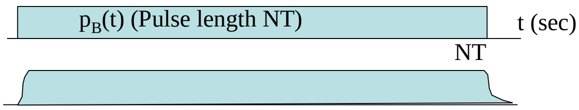
1. For dispersive channels, it is an alternative to the wideband channel equalization required in single carrier systems.

-The data pulse is N times longer than that of the single-carrier system, and thus suffers 1/N the proportional pulse dispersion. Simple phase corrections can be made in the subchannels to compensate linear channel distortion.

Single carrier system: Short pulse p(t) sensitive to dispersive distortion and thus intersymbol interference. Requires heavy-duty channel equalization.

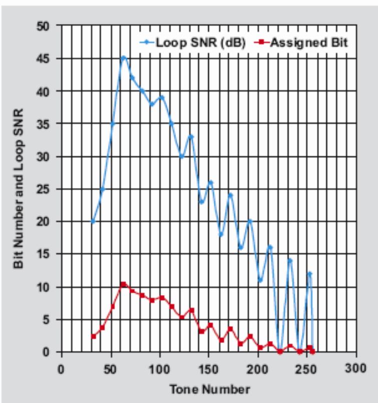


OFDM: Long pulse much less sensitive to dispersive distortion

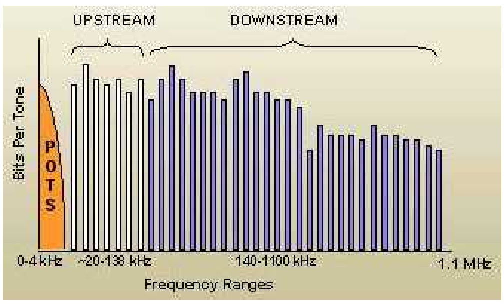


2. Traffic and power can be selectively placed in different subbands according to propagation and interference conditions, valuable flexibility for multiservice networks.

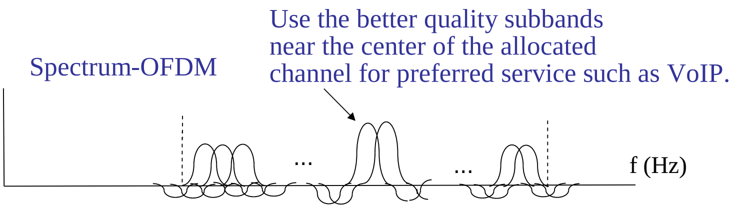
Within each subband, a variety of signaling formats can be used (e.g., binary, phase modulation, QAM), for higher or lower data rate as conditions allow.

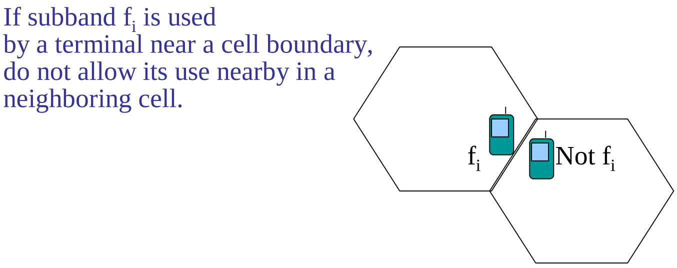


ADSL:
Channel attenuation
Rate (bits) assignment to subbands
Source: Paul Henry, AT&T Labs



Another current application: Qualcomm/Flarion cellular mobile system.





A brief history of OFDM

1. Robert Chang provided an early analysis of a multiple subband transmission system, with frequency-overlapping but orthogonal subband signals.

   Ref: R.W. Chang, "High-speed multichannel data transmission with bandlimited orthogonal signals", Bell Syst. Tech. Journal, vol. 45, Dec. 1966, pp. 1775-1796.

   Chang demonstrated orthogonal QAM subband signals, each carrying data at rate 2 ? bits/sec, spaced ? Hz apart.

2. OFDM is used by military HF radio systems in the 1960s.

Ref: Mark S. Zimmerman & Alan L. Kirsch, "The AN/GSC-10 (KATHRYN) variable-rate data modem for HF radio", IEEE Trans. on Commun. Technol., Vol. 15 #2, April 1967, pp. 197-204.

It is possible that OFDM-like systems were used even in WWII.

Zimmerman & Kirsch generated the subcarrier signals using the discrete Fourier transform in an analog hardware implementation. They claimed but did not analytically demonstrate orthogonality of the subband signals. They appear to have distributed power uniformly over all subbands.

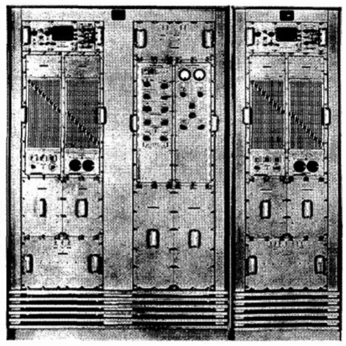


Fig. 9. AN/GSC-10 KATHRYN duplex terminal.

3. Performance analyses for OFDM systems done at Bell Labs.

Refs:

Burton R. Saltzberg, "Performance of an efficient parallel data transmission system", IEEE Trans. on Commun. Technol., vol. 15 #6, Dec. 1967, pp. 805-811.

Robert W. Chang & Richard A. Gibby, "A theoretical study of performance of an orthogonal multiplexing data transmission scheme", IEEE Trans. on Commun. Technol., vol. 16 #4, Aug. 1968, pp. 529-540.

Saltzberg investigated performance of Chang's model in a dispersive channel, assuming both intersymbol and inter-subchannel interference as well as phase offset, and alternative pulse rolloff (spectrum) characteristics. Eye opening performance criterion.

Chang & Gibby analyzed performance in the presence of sampling time error, carrier phase offset, and phase distortions in the transmitting and receiving filters, also using the criterion of eye opening.

4. Discovery that the FFT (fast Fourier transform) algorithm can be used for computationally efficient digital generation of parallel (multiple subband) data signals.

- At Bob Lucky's request, I looked into the relatively new Cooley-Tukey FFT and suggested generating parallel data signals defined by the DFT.

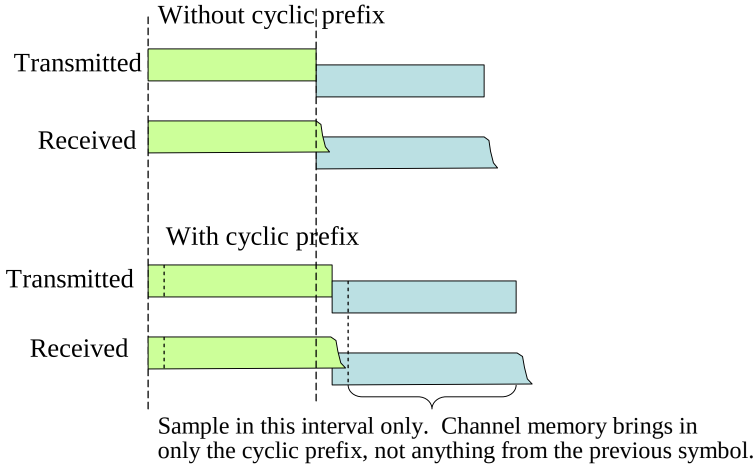
- Jack Salz, my boss, did some initial analysis and we presented a conference paper on the concept of using a digitally computed DFT and the FFT algorithm.
  Ref: J. Salz & S.B. Weinstein, "Fourier transform communication system", ACM Conf. on Computers & Communication, Pine Mountaiin, GA, Oct. 1969.

- Encouraged by Jack, Paul Ebert and I developed the ideas further, including simple subband channel equalization minimizing MSE.
  Ref: S.B. Weinstein & Paul M. Ebert, "Data transmission for frequency-division multiplexing using the discrete Fourier transform", IEEE Trans. on Commun. Technol., vol. 19 #5, Oct. 1971, pp. 628-634.

5. Use of cyclic prefix rather than windowing of OFDM pulse to avoid intersymbol interference.
   Ref: R. Peled & A. Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms", Proc. IEEE Internat. Conf. on Acoustics, Speech, and Signal Processiing, ICASSP 1980, Denver, pp. 964-967.

   An OFDM signal with a lengthened input data block (at least as much as the channel "memory") in which the added prefix repeats signal from the end of the original symbol interval.

The transmitter transmits cyclically-extended OFDM symbols (in N subbands)



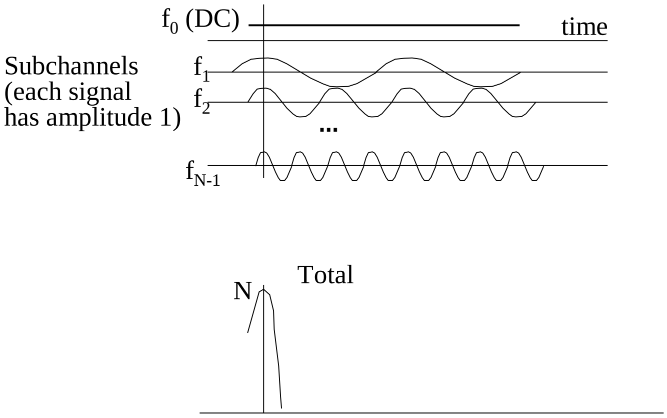
If this were a longer talk, I would present Jack Salz's "circulant matrix" explanation of how the cyclical prefix eliminates intersymbol interference in OFDM.
A popular modification (zero prefix and appropriate demodulation) is sometimes implemented.

$$\begin{pmatrix} h_0 & 0 & h_2 & h_1 \\ h_1 & h_0 & 0 & h_2 \\ h_2 & h_1 & h_0 & 0 \\ 0 & h_2 & h_1 & h_0 \end{pmatrix}$$

A circulant matrix corresponding to a dispersive channel with memory of two sampling intervals.

6. Mitigation of problem of high peak-to-average signal levels

One of the earliest identified problems with OFDM was the high peak signal for certain data sequences and subcarrier phasings. Mitigating this problem was important for practical application. OFDM is still not favored in satellite communication systems with sharply limiting power amplifiers.



References for mitigation of peak to average power (just a few of many):

L.J. Greenstein & PJ. Fitzgerald, "Phasing multitone signals to minimize peak factors", IEEE Trans. Commun., vol. 29 #7, 1981,pp. 1072-1074.

R.W. Bäuml, R.F.H. Fischer & J.B. Huber, "Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping", Electronics Letters, vol. 32, 1996, pp. 554-555.

M. Friese, "Multicarrier modulation with low peak-to-average power ratios", Electronics Letters, vol. 32, April 1996, pp. 713-714.

D. Wulich & L. Foldfeld, "Reduction of peak factor in orthogonal multicarrrier modulation by amplitude limiting and coding", IEEE Trans. Commun., vol. 47 #1, 1999, pp. 18-21

7. Computationally more efficient implementations.

A good example: B. Hirosaki's N/2 system.

Ref: Botaro Hirosaki, "An orthogonally multiplexed QAM system using the discrete Fourier transform", IEEE Trans. on Commun., vol. COM-29 #7, July, 1981.

For a passband system with QAM subband signals, if the lower end of the passband is an integer plus 0.5 times the subband spacing, an N/2 point DFT rather than an N point DFT can be used with large saving in number of multiplications and additions.

8. Application to mobile communication

Refs (among many):

L. Cimini, "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing", IEEE Trans. Commun., vol. 33 #7, July 1985, pp. 665-675.

I. Kalet, "The multitone channel", IEEE Trans. on Commun., vol. 37 #2, Feb. 1989, pp. 119-124.

Analytical and experimental investigations of OFDM performance in mobile communication channels.

There are many books on (or including) OFDM

A few of them are:

- L. Hanzo, M. Münster, B. Choi, T. Keller, OFDM and MC-CDMA, IEEE Press & Wiley, 2003.
- A. Bahai, B. Saltzberg, M. Ergen, Multi-carrier Digital Communications: Theory and Applications of OFDM, Springer, 2004.
- R. Prasad, OFDM for Wireless Communications Systems, Artech House, 2004.

Concluding Observations

The communications infrastructure is becoming both more diverse in network types and more convergent in architectures and techniques. An optical/wireless hierarchy, tuned for IP (network level) and Ethernet (PHY/MAC) is a preferred access architecture.

We will always be applying new techniques to get additional capacity and performance from the existing transmission channels and modulation choices.

OFDM is a good example of applying a computing technique to advantage in a wide variety of access communications systems.

Thank you!