

# Trends in the Effective Use of the Limited Radio Spectrum

Dr. Carl-Erik W. Sundberg

Visiting Senior Scientist,  
DoCoMo Labs, Palo Alto, California, USA  
cews@docomolabs-usa.com

# Carl-Erik W. Sundberg

## Brief Biography

- Ph.D. Lund University, Sweden 1975
- ESA Research Fellow 1976
- Research Professor, Lund University 1977-1984
- Bell Labs, USA, DMTS 1981-2000
- Agere Research, DMTS, 2001-2002, Retired.
- SundComm, President and Chief Scientist, 2001-
- iBiquity Digital Systems, 2002-2004
- Visiting Professor, Korea University, part of 2003, 2004 and 2005
- Visiting Senior Scientist, DoCoMo Labs, USA, 2006-
- Fellow IEEE 1990, Life Fellow 2008.
- Guest editor: Coded Modulation Systems, IEEE JSAC , 1987-1988
- Guest editor: 4G Wireless Systems, IEEE JSAC, 2005-2006
- Listed in Who's Who in America
- 3 Books, 111 journal papers, 155 conference papers, 120 patents.
- 2 Best paper awards, 1 Best conference paper award
- 2 Papers on the list of the 56 most important papers published by IEEE COMSOC 1952-2002 (50<sup>th</sup> anniversary journal paper collections). Published in "Best of the Best", IEEE Press/Wiley 2007.

- CPM (Continuous Phase Modulation) and Coded CPM
  - Used in 2G GSM
- Circular Viterbi Tailbiting Decoder
  - Used in 2G IS54 (US TDMA)
- CPPC codes
  - Used in US FM HIBOC DAB (HD Radio)
- Multi-streaming
  - Used in US AM HIBOC DAB, (HD Radio)
- Joint Multiple Program Audio Coding and Transmission
  - Used in Sirius Satellite Radio
- LVA, MLLA, LMAP decoders
  - Option of list decoder in HD Radio

# Outline

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- Spectrum as a limited natural resource.
- First Analog then Digital Methods and Technology.
- Information and Coding Theory.
- Frequency reuse in the spatial domain.
- Spatial Multiplexing, MIMO.
- Multi Antenna Technologies.
- Cellular Convergence 3G MBMS and 4G MBMS+
- Regulations.
- Cognitive Radio.
- White Space Radio.
- Examples of Wireless Services.
- Some New Wireless Services.
- Conclusions.

# Basic Principles

- Information and Coding Theory.
- Claude Shannon, BSTJ 1948.
- $R < C = W \log(1 + S/N)$ .
- Rate/Distortion theory.
- Spatial Multiplexing.
- MIMO, Space Time Coding.
- Frequency Reuse. Handover.
- Cellsplitting.
- Femtocells.
- Relays.
- Dirty Paper Coding.
- Cognitive Radio.

# Digital Communication System

- Source Encoder      A/D, Compression
  - Channel Encoder    LDPC, Turbo Codes etc
  - Bit Interleaver     Bit Scrambling
  - Modulator          QPSK, 16QAM, 64QAM, CPM
  - Channel             Noisy Fading Channel
  - Demodulator        Soft Output
  - Bit Deinterleaver   Soft Deinterleaver
  - Channel Decoder    Soft Decoding, Iterative
  - Source Decoder     D/A
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- Joint source and channel coding, UEP
  - Combined Coding and Modulation, BICM

# Digital Transmission, Why?

- Efficiency in the Use of Spectrum and Power.
- Higher Quality, Robust Quality.
- Flexibility.
- Signal Processing Advantages.
- Multiplexing, Datacasting.
- Security, Encryption.

# Properties of electromagnetic waves

- Different frequencies have different properties.
- Different suitability for applications.
- Attenuation, scattering, propagation, directivity, coverage, range, reflections in outer ionosphere, etc.
- Lower frequencies: Larger coverage, smaller bandwidth.
- Higher frequencies: Shorter range, much larger bandwidth, increasingly more like optical properties.

# Radio Spectrum Chart

- 10-30 kHz Very Low Frequency, VLF
- 30-300 kHz LF
- 30 kHz-3 MHz MF
- 3-30 MHz HF
- 30-328.6 MHz Very HF VHF
- 328.6 -450MHz-2.9 GHz Ultra HF, UHF
- 2.9-30 GHz Super HF, SHF
- >30GHz Extreme HF, EHF
- >300GHz Amateur

# Wavelength and Frequency

- $\lambda = c/f$ ,  $c = 300,000,000$  m/sec
- Frequency      Wavelength
- 10kHz            30000 m
- 100 kHz        3000 m              LW Radio
- 1 MHz            300 m                MW Radio, AM
- 10 MHz          30 m                 SW Radio
- 100 MHz        3 m                  FM Radio
- 1 GHz            0.3 m or 3 dm     Cellular Wireless
- 10 GHz          0.03 m or 3 cm
- 100 GHz        0.003 m or 3 mm
- 300 GHz        0.001 m or 1 mm
- 1000 GHz, 1 THz    0.3 mm or 300,000 nm , Radio ends at 300 GHz ?
- 10,000 GHz ,10 THz 0.03 mm or 30,000 nm , IR
- 100 THz         3000 nm or 30,000 A        , IR
- 1000THz ,1PHz    300 nm or 3000 A , UVL, VL 4000-7000 A , (571-750 THz).
- 10 PHz            30 nm or 300 A,        UVL
- 100 PHz          3nm                 X Ray, 0.01 nm-10 nm, (30-30,000 PHz).

# Extremes of Radio

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- Carrier Frequency 17.2 kHz, 17 km
- Grimeton, Sweden 1924
- 60,80,90 GHz applications
- 480 GHz now discussed

# Media Source Coding Methods

- Audio
  - MPEG-1, MP2, Musicam, MPEG-2, MP3, Dolby AC-3
  - PAC/Multi-program (proprietary coding for Sirius Satellite Radio)
  - AAC, AAC+/SBR, HE-AAC/PS
  - Bitrates compressed from 1.4 Mb/s (CD Stereo) to a range of 128 kb/s to 24 kb/s
  - HD-AAC bitrates compressed from 4.5 Mb/s to a range of 384 kb/s to 128 kb/s
  
- Speech
  - Broadcasting requires coders for speech and music, i.e. audio coders
  - For cellular, good speech coders at 6-16 kb/sec
  - Wideband speech HQ 32 kb/sec
  - VOIP special requirements
  
- Video
  - MPEG-1, MPEG-2, MPEG-4/Part 2
  - H.262, H.263, H.264 (MPEG-4/Part 10 or AVC)
  - Bitrates are compressed
    - from 2 Gb/s to 10 Mb/s (for a large screen)
    - from 30 Mb/s to 200 kb/s (for a small screen)
  
- Internet
  - Real Player
  - Windows Media Player
  - Adobe Flash Player
  - GIPSolutions, VOIP, Skype

# Terrestrial Digital Audio Broadcasting

- The United States
  - HD-Radio, HIBOC-FM, HIBOC-AM
  - MediaFLO (700 MHz Band, 4096 OFDM, QPSK or 16 QAM, HE-AAC)
- Europe
  - DAB Eureka 147, DAB+ (OFDM,SFN,AAC+)
  - DVB-H
  - DVB-T
- Japan
  - ISDB-T
  - ISDB-T,1seg
- China and Korea
  - T-DMB
  - DMB-T/H
- Global
  - DRM (Digital Radio Mondiale): SW, AM, FM

# Terrestrial Digital TV Broadcasting

- The United States
  - ATSC (6 MHz, 8 VSB, 19.39 Mb/s, Dolby AC-3)
  - MediaFLO (700 MHz Band, 4096 OFDM, QPSK or 16 QAM, 200 kb/s video, HE-AAC)
- Europe
  - DVB-H
  - DVB-T
- Japan
  - ISDB-T
  - ISDB-T,1seg
- China and Korea
  - T-DMB
  - DMB-T/H

# Technology Building Blocks

- Digital modulation techniques
  - Coded OFDM
  - BICM
  - 8VSB AM Single Carrier (ATSC only)
  - QAM Modulation (2QAM, 4QAM, 16QAM, 64QAM, 256QAM)
  - Layered/Hierarchical Modulation
- Channel codes
  - Interleaving
  - Convolutional Codes
  - Turbo Codes
  - CPPC Codes (HD Radio FM)
  - Cyclic Redundancy Check (CRC) Codes and Error Mitigation
  - Reed Solomon Codes
- Single Frequency Network (SFN) with Multiple Transmit Antennas

# HD Radio: The IBOC Concept

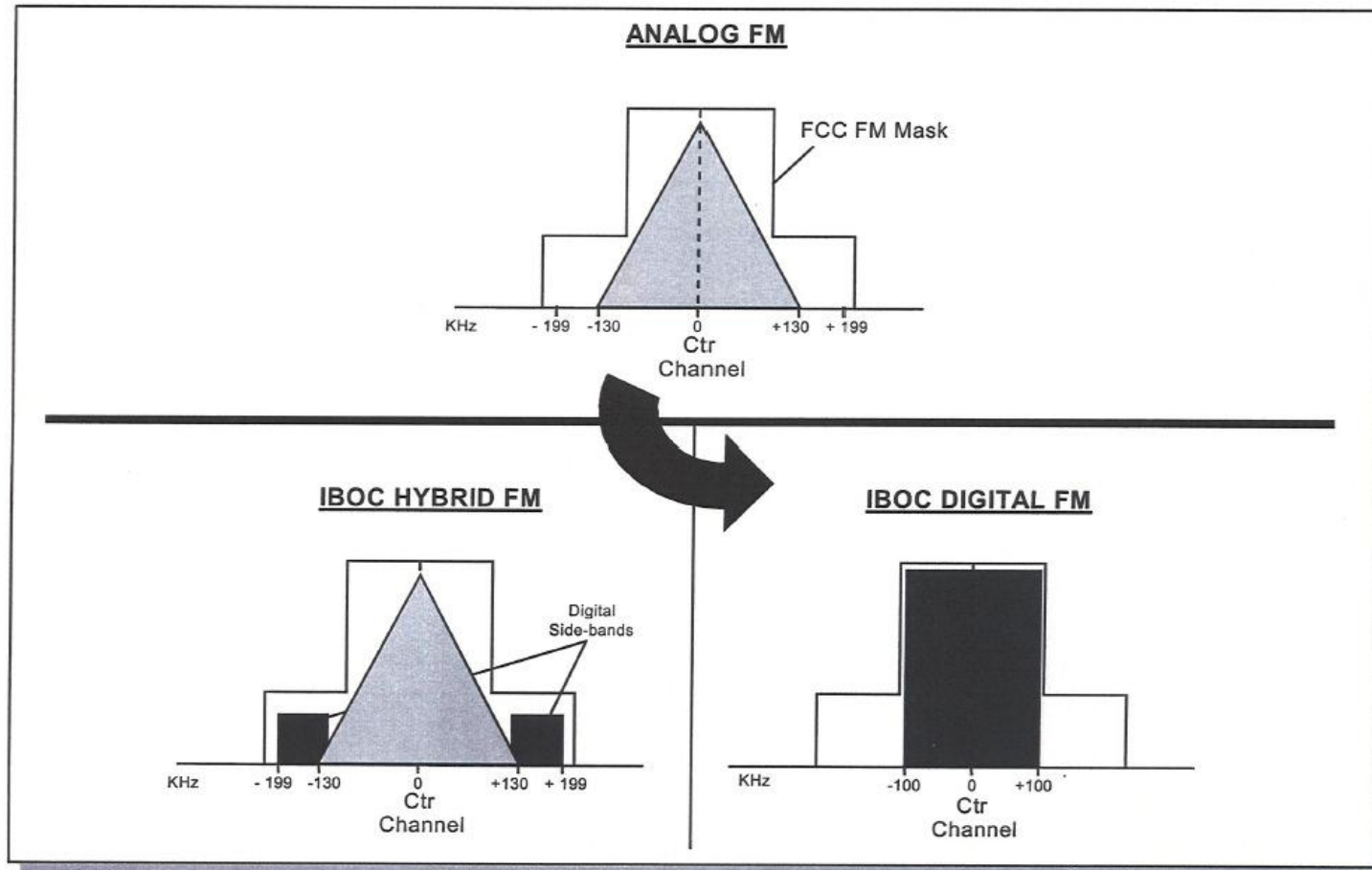
- In Band On Channel (IBOC) Systems
- IBOC is now referred to as HD Radio
- Digital and analog broadcasting coexist simultaneously in the FM and AM bands
- Now hybrid (HIBOC); in the future all digital IBOC
- iBiquity Digital Corporation provides the HD Radio Technology ([www.ibiquity.com](http://www.ibiquity.com))

C-E. W. Sundberg *et al.*, "Technical advances in digital audio radio broadcasting," Proceedings of IEEE, pp. 1303-1333, Aug. 2002

# Status of HD Radio (2008)

- US Standard
  - NRSC (National Radio Systems Committee), NAB, CEA, EIA
  - FCC
- Was introduced in 2003, but work started around 1990
  - 1 million receivers in the US (84 different models)
  - About 1700 stations for AM (500) and FM (1200) in the US (2007)
  - About 200 HD2 stations (April 2006) and a few HD3 stations
  - See [www.ibequity.com](http://www.ibequity.com) and [www.hdradio.com](http://www.hdradio.com) for details
- Multicasting 1 (HD), 2 (HD2) or 3 (HD3) digital programs
  - Net bit rate 100-150 kb/sec depending on system modes
- Datacasting: Text-based information, weather, school-closings etc
- Tests in: France, Thailand, Philippines, Brazil, Hong Kong Switzerland, New Zealand, Canada, Mexico, Australia etc.
- In vehicles as standard 2010: Jaguar, Mercedes, Lincoln, Volvo, Audi etc

# From Analog to IBOC



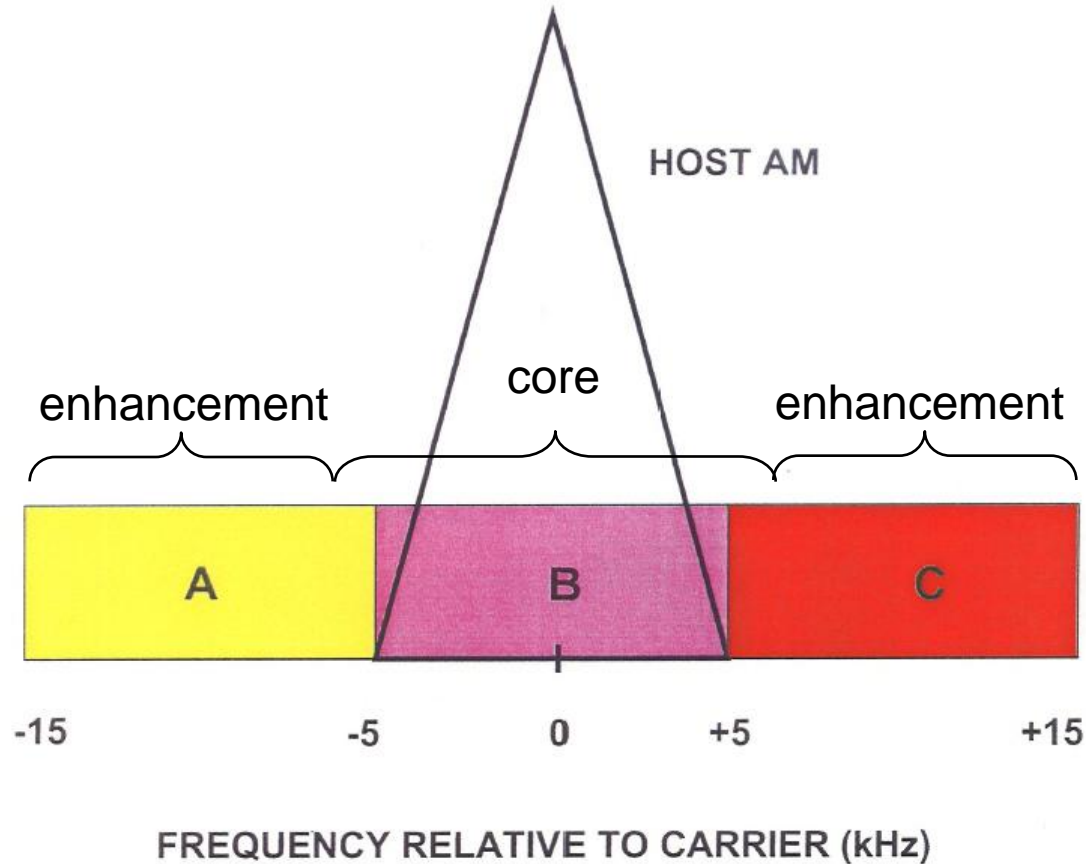
Analog FM, Hybrid and All Digital IBOC

# Dirty Paper Coding (DPC)

- M. Costa, “Writing on Dirty Paper,” IEEE Trans. on Information Theory, May 1983
  - $y = s + n$ ,  $C = 0.5 \log(1 + S/N)$   $s$  = desired signal,  $I$  = interference
  - $y = s + I + n$ ,  $C = 0.5 \log(1 + S/N)$   $n$  = noise,  $y$  = received signal
  
- Applications to:
  - Watermarking
  - Precoding for MU-MIMO
  - DAB, simultaneous transmission of analog FM and digital HD Radio, FM HIBOC with increased data rate

H. C. Papadopoulos and C-E. W. Sundberg, “Pre-coded modulo-precanceling systems for simulcasting analog FM and digital data,” IEEE Trans. on Communications, *August 2008*

# AM Hybrid IBOC



Hybrid IBOC AM power spectrum example

# AM HD Radio HIBOC Details

- 30 kHz bandwidth, analog host 10 kHz
- 3 sub-bands (10 + 10 + 10 kHz)
- Simultaneous Analog AM and Digital in 10 kHz
- OFDM
- Multi-stream transmission
- 2 QAM (BPSK), 4 QAM, 16 QAM, 64 QAM
- Embedded AAC+/SBR stereo coding (24-48 kb/s stereo)
- TCM with outer Reed Solomon coding
- Advanced soft combining

# Technologies not (yet) used for broadcasting

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- Multiple Antenna Technologies combined with advanced signal processing
- SU-MIMO
- MU-MIMO
  
- However, MISO multiple transmit antenna SFN is used in DAB Eureka 147 and MediaFLO
- MISO SFN can also be used for the future All Digital IBOC HD Radio systems

# Example: “4G” SU-MIMO

- System Bandwidth 100MHz
- Single Cell
- Low Mobility
  
- CSIR (channel state information at the receiver), Open Loop
- 12x12 Transmit and Receive Antennas, 144 channels
- BICM, 64 QAM, high rate outer code
- Complex receiver
- **5 Gb/s** data rate
- **50 b/s/Hz** spectral efficiency
- Test system built by DoCoMo

H. Taoka *et al.*, “Field experiments on ultimate frequency efficiency exceeding 30 bit/second/Hz using MLD signal detection in MIMO-OFDM broadband packet radio access,” Proc. IEEE VTC, pp. 2129-2134, Mar. 2007

O.Y. Borsalioglu, H.C. Papadopoulos and C-E. W. Sundberg, “Reduced-complexity adaptive receiver algorithms for 4G SU-MIMO systems,” IEEE VTC 2008 Fall, September 2008.

H.C. Papadopoulos and C-E.W. Sundberg, “Iterative SU-MIMO Receivers based on SOMA Demappers with Improved Survivor Selection”, PIMRC2009, Tokyo, Japan, September 2009.

# Example: “4G,5G” MU-MIMO

- System bandwidth: 100 MHz
- Single cell
- Low mobility
- CSIR and CSIT (channel state information)
- Channel Reciprocity and TDD
- $N = 150$  transmit antennas, 150 channels/user
- $K = 75$  users, each with 1 antenna
- Simple receivers for the mobiles
- Linear precoding at the transmitter
- 64 QAM, 400 Mb/s per user
- **30 Gb/s** system (total rate)
- **300 b/s/Hz** spectral efficiency

K. Gomadam, H.C. Papadopoulos and C-E. W. Sundberg, “Techniques for multi-user MIMO with two-way training,” ICC2008, Beijing, China, May 2008.

# Continuous Phase Modulation (CPM)

- Constant amplitude, PAPR = 1 (0 dB)
- Partial response, modulation index  $h$
- Nonlinear in nature, except for binary schemes with short partial response pulses and modulation index  $h = \frac{1}{2}$ 
  - These schemes are approximately linear
- General receiver is a Viterbi decoder
- Equalization is in general problematic
- Combined coding and CPM
- GMSK is a special case (used in 2G GSM)
  - Binary partial response scheme with a Gaussian pulse in instantaneous frequency and  $h = \frac{1}{2}$
- **Alternative All Digital CPM based IBOC systems have been designed and tested**

T. Aulin, J.B. Anderson and C-E. W. Sundberg, "Digital Phase Modulation", Plenum, New York, 1986

# Example: CPM IBOC FM

- 200 kHz Bandwidth
- Constant amplitude CPM signal
- High power transmission with existing FM transmitters
- GMSK 1.2b/s/Hz (GSM modem)
- $R=2/3$  channel coding
- 150 kb/s net bit rate
- UEP
- AAC+/SBR 48-64 kb/s
- Several possible system modes:
  - 2 music programs plus data
  - 1 music program, 1 talk program plus data
  - 3 talk programs plus data

# Convergence with Cellular

- One radio
  - 3G WCDMA: MBMS (Multimedia Broadcast and Multicast Service) with soft combining
  - 4G LTE: OFDM, MBMS with SFN
  - 4G LTE-A, IMT-A: OFDM, MBMS+ with MIMO?
  - Broadcasting and Multicasting
- Two Separate radios
  - HD Radio
  - MediaFLO
  - DVB-H
  - DAB Eureka, DAB+

# Future Wireless Broadcasting?

- Video
  - UHDTV NHK test system
    - 24 Gb/s compressed to 180-600 Mb/s
  - 3D HQ Video
  - MVC, multiple view coding
- Audio
  - HQ Audio perhaps with HD-AAC at 384 kb/s
  - Multi channel systems
  - Spatial audio/3D audio
- Multicasting over cellular with MBMS++
- Cable/fiber/satellite distribution to stationary users
- Internet streaming
- P2P streaming

# Cellular service

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- 1G analog, AMPS, NMT-450, NMT-900
- 2G GSM, IS95 CDMA , IS54 TDMA etc
- 2.5G GPRS, Edge
- 3G WCDMA,UMTS, HSPA, HSPA+, etc
- WiMAX
- 3.9G,4G LTE
- 4G LTE-A, IMT-A
- 5G? Evolution from LTE-A?
- 6G?.....

# MIMO Technologies for Wireless

- LTE 4x4 SU-MIMO DL
- LTE-A 8x8 SU-MIMO DL
- LTE-A 4x4 SU-MIMO UL
- LTE-A MU-MIMO, NW-MIMO
- WiMAX 4x4 SU-MIMO DL
- 802.11n 4x4 SU-MIMO

# LTE-Advanced

- Spectrum Aggregation
- Spatial Multiplexing/MIMO
- Relays

# Wireless LAN Service

- LAN, e.g. 802.11n.
- MAN
- WAN
- PAN
- BAN, MBAN

# Cognitive Radio

- Some spectrum is used inefficiently.
- Three paradigms for Cognitive Radio.
- Interweave (Original, Opportunistic), Overlay (DPC), Underlay (UWB).
- Spectrum Sensing.
- Spectrum Management
- Spectrum Sharing.
- Regulations required.
- Spectrum reuse, joint use.
- Licensed Band Cognitive Radio 802.22.
- Unlicensed Band Cognitive Radio 802.15.
- Cognitive Radio Equipment is more complex and expensive, requires more power.

# White Space Spectrum

- Analog TV shut down.
- Vacated bands used for unlicensed LAN.
- Over the air TV service moved to cable.
- NMT-450 bands have new use.

# Regulatory Issues

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- Licensed Spectrum, FCC.
- Unlicensed Spectrum, WIFI, IEEE 802.
- NAB, NRSC, EIA, CEO.
- 3GPP, IMT, ITU-R.
- ETSI.
- ATIS, CCSA, TTA, ARIB, TTC
- ISO.

# Wireless services

- Broadcasting, TV and Radio
- Cellular
- Wireless LAN, MAN, WAN, PAN and BAN
- Satellite
- Paging
- Point to point radio links
- RFID
- Military
- Aviation
- Radar
- Cordless phones
- Radio Astronomy
- Amateur radio
- CB Radio
- Navigation
- GPS
- Maritime radio
- Time frequency standards
- Etc

# Examples of Heavy and Light Users

- Heavy Users
  - Cellular
  - Broadcast services
- Light Users
  - Amateurs
  - Paging
  - Some military use?

# Examples of Recent Wireless

- RFID
  - Smart cards
  - Animal Tracking
  - Library Books
  - Airline Baggage
  - Carton Tracking
- BAN, MBAN
  - Body Area Network
  - Medical monitoring
- Bluetooth
  - Replacing wires
  - Named after a Viking King, Harald Bluetooth
  - 2.4 GHz, up to 10m, up to 1Mb/s.
- Public response radio
  - Police, Firefighters etc on the same radios. Digital mobile radio

# Examples of Future Heavy Users

- 5G, 6G cellular, wireless internet
  - Social networks
  - User generated content
- Broadcasting
  - HQ 3D Video
  - HQ Radio
- Machine to machine communication, M2M.
- P2P?
- Client/server Traffic?
- Security/Surveillance?
- Electronic Books and Papers?

# Discussion and Conclusions

- Frequency Spectrum Limited Natural Resource
- Increasing number of Wireless services
- Digital encoding and transmission vs analog
- Frequency reuse
- Spatial Multiplexing
- Higher Frequencies
- Cognitive Radio
- New Regulations
- New use of spectrum: NMT-450 and Analog TV Bands Vacated

# References

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- C. E. Shannon, “A Mathematical Theory of Communications”, BSTJ 1948
- A. Goldsmith et al, “Breaking Spectrum Gridlock with Cognitive Radios: An Informationtheoretic Perspective”, 2008.
- P. Mitran, “Cognitive Radio: A Survey”, February 2008.

# References

- [www.ibiquity.com](http://www.ibiquity.com)
- C-E.W. Sundberg et al. “Technical advances in Digital Audio Radio Broadcasting”, Proc. Of the IEEE, August 2002
- H.C. Papadopoulos and C-E. W. Sundberg, “Precoded Modulo-Precancelling...”, IEEE Trans. COM, 2008.
- C.F. Leanderson and C-E. W. Sundberg, “MLLA MaxLogList Algorithms.....” and other List Algorithms, IEEE Trans. COM, 3 papers 2005.

# Ultra Wideband, UWB

- Low power, very large bandwidth.
- Little or no interference with traditional radio in the band.
- Short distance applications.
- Underlay Cognitive Radio Paradigm.

# Auctions

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- Pricing issues
- Quality vs price

# Emphasis in this talk

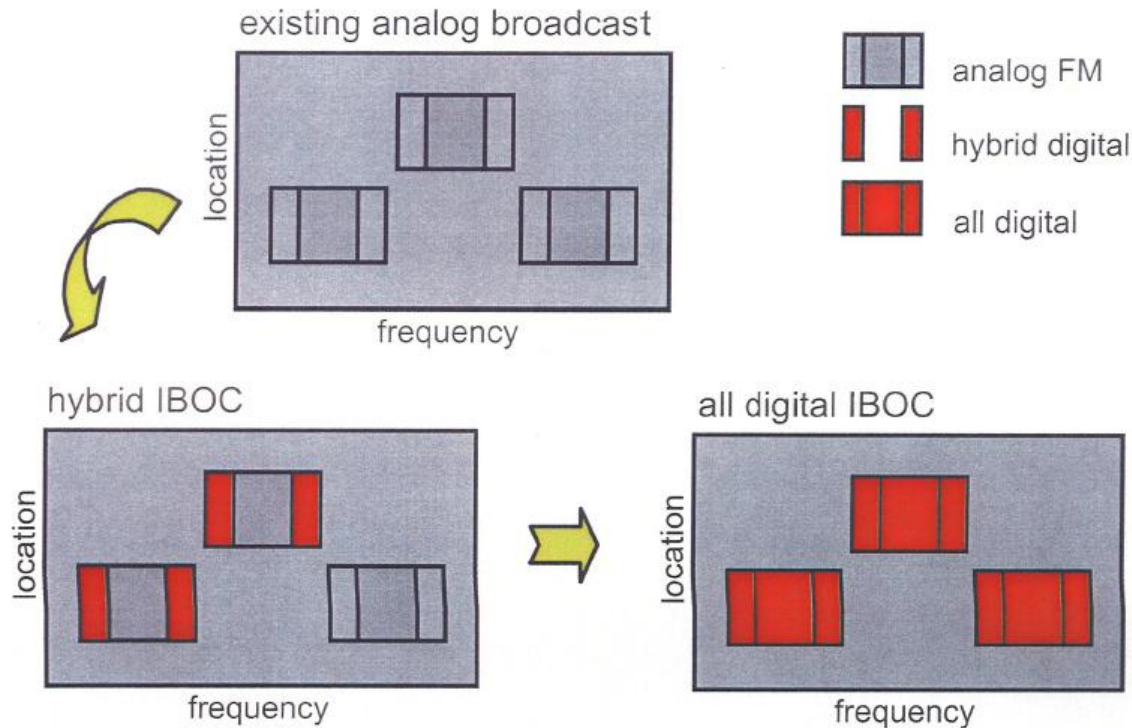
- Radio Spectrum is a Limited Natural Resource.
- Fundamental Principles for Spectral Efficiency.
- Digital more efficient than Analog.
- Technology
  - Media Source Coding and Compression.
  - Digital Modulation and Channel Coding.
  - MIMO and Spatial Multiplexing.
  - Frequency Reuse.
  - Dirty Paper Coding.
  - Cognitive Radio
- Regulation and Pricing.
  - Regulated and Unregulated Spectrum
  - Licensed and Unlicensed Spectrum
  - Migration of Services
  - Auction/Pricing

# IBOC FM HD Radio

- 400 kHz bandwidth
- 70 + 70 kHz for Digital HIBOC
- FCC emission mask
- Co-channel, 1<sup>st</sup> and 2<sup>nd</sup> Adjacent Channel
- Digital 25 dB below Analog FM

# Frequency Reuse IBOC

## In-Band-On-Channel DSB



Analog, Hybrid and Digital IBOC Frequency Reuse