Spektrum, unser wertvollstes Gut
oder was ist eigentlich spektrale Effizienz und wie können wir sie steigern?

Spectrum, our most valuable asset
or what is spectral efficiency and how can we raise it?

Prof. Dr.-Ing. Georg Fischer
Lehrstuhl für Technische Elektronik

The birthplace of
Prof. Georg Fischer (geb. 1965)

1986-1992 Study of Electrical Engineering at RWTH Aachen (Aix La Chapelle) Focus on Communications, Radio Technology, Field Theory

1993-1996 Research assistant at University of Paderborn Fachgebiet Nachrichtentechnik, Prof. Dr. Wido Kumm

1997 Dr.-Ing., Thesis „Adaptive Antenna Arrays for mobile satellite reception“

1996-2008 Lucent, later Alcatel-Lucent, Bell Labs Research Research on Basestation RF Technology 2000 Bell Labs DMTS (Distinguished Member of Technical Staff) 2001 Bell Labs CMTS (Consulting Member of Technical Staff) Chairman of ETSI SMG2 WPB EDGE

2001-2007 Part time Lecturer at University of Paderborn

April 2008 University of Erlangen-Nürnberg Prof. for Electronics Engineering Research on Cognitive Radio, Frequency Agile Radio, Analog-Digital Balance

Since 2010 ETSI STF 386 Chairman „Methods, parameters and test procedures for cognitive interference mitigation techniques for use by PMSE devices“
1. Evolution of Wireless Data Traffic
2. What is the value of spectrum?
3. Spectrum situation at UHF
4. Communications model
5. Communication link
6. Spectral Efficiency - what is it?
7. Spectral efficiency - How to raise it?
8. Conclusions
1. Evolution of Wireless Data Traffic
Evolution of Wireless Data Traffic
ITRS Roadmap for Microelectronics

Moore’s Law & More

Traditional ORTC Models

Functional Diversification (More than Moore)

- Analog/RF
- HV Power
- Passives
- Sensors
- Actuators
- Biochips

Interacting with people and environment
Non-digital content System-in-package (SiP)
Combining SoC and SiP: Higher Value Systems
Beyond CMOS

Scalability (More Moore)
Geometrical & Equivalent scaling, Baseline CMOS: CPU, Memory, Logic

130nm
90nm
65nm
45nm
32nm
22nm
V

Ever higher resolution Sensors and Actors for A/V enable immersive perception!

Source: INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS (ITRS) 2009 EDITION
Evolution of Wireless Data Traffic
Moore’s law in microelectronics

Gordan Moore, TI
1965: “Complexity of an IC is doubling every 2 years”

Moore’s law: Integration density of Electronics is doubling every two years

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Evolution of Wireless Data Traffic
Growth of wireless data amount

Figure 1. Cisco Forecasts 6.3 Exabytes per Month of Mobile Data Traffic by 2015

Terabytes per Month

<table>
<thead>
<tr>
<th>Year</th>
<th>Terabytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0.24 EB</td>
</tr>
<tr>
<td>2011</td>
<td>0.6 EB</td>
</tr>
<tr>
<td>2012</td>
<td>1.2 EB</td>
</tr>
<tr>
<td>2013</td>
<td>2.2 EB</td>
</tr>
<tr>
<td>2014</td>
<td>3.8 EB</td>
</tr>
<tr>
<td>2015</td>
<td>6.3 EB</td>
</tr>
</tbody>
</table>

Source: Cisco VNI Mobile, 2011

⇒ CISCO law: Wireless Data amount nearly doubling each year!
Evolution of Wireless Data Traffic
Edholm’s law of bandwidth

Wireless data rates are growing faster than wireline!
We will run into a serious problem!

Source: Steven Cherry, Edholm’s Law of Bandwidth, Telecommunications data rates are as predictable as Moore’s Law, IEEE Spectrum, July 2004
Phil Edholm, Nortel’s chief technology officer and vice president of network architecture
Evolution of Wireless Data Traffic
Edholm’s law of bandwidth

Edholm’s law: „Data Rates are as predictable as Moore’s law“ doubling every two years
Evolution of Wireless Data Traffic
Data amount by device

Figure 3. Laptops and Smartphones Lead Traffic Growth

Petabytes per Month

Source: Cisco VNI Mobile, 2011

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Laptops and Smartphones with QuadCore and HD Display…
Evolution of Wireless Data Traffic
Terminals are the driver

Figure 4. High-End Devices Can Multiply Traffic

- Smartphone = x 24*
- Handheld Gaming Console = x 60*
- Tablet = x 122*
- Mobile Phone Projector = x 300*
- Laptop = x 515*

* Monthly basic mobile phone data traffic

Source: Cisco VNI Mobile, 2011

Wish for immersion leads to higher data rates on Production and Distribution
Evolution of Wireless Data Traffic
Wish for immersion

Video
HDTV, 3D, HD, UHD, HDR, 4k, 8k,

Audio
Surround sound, studio quality, DTS, HD Audio, Dolby 5.1, Dolby ATMOS

High data rates apply to production and distribution

Cinema, Shaking, 4D

Source: Star Trek

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Evolution of Wireless Data Traffic
What we do so far...

Linear Assignment of Spectrum

Exponential growth of data

It is impossible to satisfy exponential data traffic growth by assigning spectrum linearly!

How to fill the gap coming up?

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Evolution of Wireless Data Traffic

Exponential growth

It is impossible to satisfy an exponential traffic growth by linearly adding more spectrum

Do you know the fairy tale?
1 rice corn on the first field, then
2, 4, 8,16, 32, 64, 128, 256, 512, 1024, 2048, ...

There is rumour 400…6000 MHz will all become Mobile communication…
Giving more spectrum in a linear way will not satisfy Mobile demand…

Total spectrum needs to double after each DD?
Yearly Digital Dividends? Doubling total spectrum …..impossible….
Multichannel law: # of audio channels with audio format in the past doubling every 20 years, now quicker growth rate
**Evolution of Wireless Data Traffic**

**Eurovision Song Contest**

<table>
<thead>
<tr>
<th>Year</th>
<th>City / Country</th>
<th>PMSE Links</th>
<th>IEM Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Birmingham / UK</td>
<td>40 ch Mic+</td>
<td>2 ch IEM</td>
</tr>
<tr>
<td>1999</td>
<td>Jerusalem / Israel</td>
<td>42 ch Mic+</td>
<td>6 ch IEM</td>
</tr>
<tr>
<td>2000</td>
<td>Stockholm / Sweden</td>
<td>48 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2001</td>
<td>Copenhagen / Denmark</td>
<td>48 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2002</td>
<td>Tallinn / Estonia</td>
<td>54 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2003</td>
<td>Riga / Latvia</td>
<td>54 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2004</td>
<td>Istanbul / Turkey</td>
<td>54 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2005</td>
<td>Kyiv / Ukraine</td>
<td>54 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2006</td>
<td>Athens / Greece</td>
<td>54 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2007</td>
<td>Helsinki / Finland</td>
<td>56 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2008</td>
<td>Belgrade / Serbia</td>
<td>56 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2009</td>
<td>Moscow / Russia</td>
<td>56 ch Mic+</td>
<td>16 ch IEM</td>
</tr>
<tr>
<td>2010</td>
<td>Oslo / Norway</td>
<td>72 ch Mic+</td>
<td>32 ch IEM</td>
</tr>
<tr>
<td>2011</td>
<td>Düsseldorf / Germany</td>
<td>82 ch Mic+</td>
<td>40 ch IEM</td>
</tr>
<tr>
<td>2012</td>
<td>Baku / Aserbaijan</td>
<td>104 ch Mic+</td>
<td>40 ch IEM</td>
</tr>
</tbody>
</table>

**PMSE law:** Number of PMSE links doubling every 5 years
What’s going on? - Challenges of the future

Findings

Growth laws

• **Moore’s law**: Microelectronics integrations density - doubling every 2 years
• **Edholm’s law**: Data rate on interfaces – doubling – doubling every 2 years
• **Cisco law**: Data amount in mobile communication – doubling every 1 year
• **Multichannel audio law**: audio formats in the past doubling every 20 years, now quicker growth rate
• **PMSE law**: PMSE links - doubling at least every 5 years, probably faster

Finding

• Production and distribution have their growth laws
• Driver: Microelectronics and wish for Immersion

High momentum for growth with distribution and thus also production!
2. What is the value of spectrum?
What is the value of spectrum?

Radio Spectrum

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>3 GHz</td>
</tr>
<tr>
<td>1 cm</td>
<td>10 GHz</td>
</tr>
<tr>
<td>1 mm</td>
<td>30 GHz</td>
</tr>
<tr>
<td>100 μm</td>
<td>100 GHz</td>
</tr>
</tbody>
</table>

Microwaves
- Mobile phone
- Microwave oven

Millimeter waves
- On-vehicle radar

Terahertz waves
- Radio astronomy

Optik

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What is the value of spectrum?
Legendary UMTS Auction 2000

Value of spectrum: 98.8 Mrd DM for 60 MHz paired
⇒ 1,6 Milliarden DM/MHz
⇒ 800 Mil€/MHz
What is the value of spectrum?
April 2010 auction

Value of spectrum: 3.6 Mrd € for 30 MHz paired
⇒ 120 Mil €/MHz

Surprisingly, it only decayed 6x...

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What is the value of spectrum?
Comparison of auction results over years

Auction result / (Mil€/MHz)

Year

Auction: UMTS

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Price per MHz

- Strange…at 2000 MHz price went down…
- Strange…at low frequency (LTE bands) 700/800 MHz price went down
- Strange…at 1800 MHz price went up although propagation worse

Analysis

- Is there really a shortage of spectrum?
- We have auctioned spectrum too early…selling silver spoons
- Pressure on PMSE to get out of UHF is not justified to this extend by now
3. Spectrum situation at UHF
Spectrum situation at UHF
Spectrum lost for PMSE and TV

What goes on?
• Will we have one system in future that does all? 5G?
• Media convergence? Cellular, Broadcast, PMSE?

TV primary, PMSE secondary

GMS/UMTS/LTE
UL
DL

f/MHz

470 502 694 790 862 880 915 925 960

Digital Dividend I
-20%
Mobile Communication
co-primary to TV

Digital Dividend II
-24%

Further Digital Dividend -8%

PSS Public Safety and Security
e.g. TETRA

Σ -52%

If primary assignment is lost, secondary is also immediately lost

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### Spectrum situation at UHF
Why are low frequencies that valuable?

#### Pros and cons of Frequency bands

<table>
<thead>
<tr>
<th>Low frequency band</th>
<th>High frequency band</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Low propagation loss</td>
<td>- High propagation loss</td>
</tr>
<tr>
<td>- Large cell range, Bad isolation between cells</td>
<td>- Cell range limited, Large isolation between cells</td>
</tr>
<tr>
<td>- Less Doppler effect, High mobile speed supported</td>
<td>- Large Doppler effect, Max mobile speed limited</td>
</tr>
<tr>
<td>- Small bandwidth, less capacity</td>
<td>- Large bandwidth, high capacity</td>
</tr>
<tr>
<td>- Less transmit power, less emission</td>
<td></td>
</tr>
</tbody>
</table>

*Most valuable from coverage and emission point of view*

*Most valuable from capacity point of view*
Planning a cellular network

- **Power/Energy**
- **Costs**
- **Coverage** (Cell radius)
- **Capacity** (Spectral efficiency, ROI on spectrum license)

```plaintext
Totally Contradicting?
Dilemma?

→ NO !!

We need to optimize the network!
```
Spectrum situation at UHF
Network planning – a sensitive business…

0.5 dB less means 10% less cell area and 10% more base stations to invest

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Spectrum situation at UHF
Attractiveness of low frequencies

Lower frequencies

• Strong interest by Mobile Communication Network operators to lower frequency, as network rollout costs are dramatically lower

• Reason
  - Cutting frequency to half: f ½
  - Link Budget improved by: 7...10 dB
  - Cell Radius: x 1.7...2.15
  - Cell Area: x 2.9...4.64 (+193...365%)
  - Saving of cell sites: -66...-78%
  - Investment only 33...21%

• Initial network deployment at a fraction of costs when lowering frequency
• Better penetration into buildings, wall loss lower, stronger reflections
• Wireless internet in rural areas
• Better support for high mobility e.g. ICE train
Spectrum situation at UHF

Players...

Interested parties in UHF spectrum

- Cellular operators
- Broadcasters
- PMSE (Wireless Microphones, Cultural and Creative Industry)

Digital Dividend

- When TV switched from analogue to digital transmission, 4…6 digital channels fit into one analogue channel – A spectral efficiency increase?
- Part of spectrum now was given to cellular, government earned a lot of money from spectrum auction…
- Some want to repeat the game again… (Digital Dividend III ??)
4. Communications Model
We are only transmitting symbols (not bits!) and need to negotiate upfront what this means…
Communications Model
Information theoretical view

Model
• Information from a communication source is sent to a communication sink
• Only transinformation is transported over a wireless link

If we minimize transinformation, we need less spectrum!
The big temptation…

- The less transinformation, the less spectrum need
- Identify more irrelevance and redundancy in our information source…
- The more we compress, the less spectrum is needed

Big brother

- Somebody is deciding what is irrelevant information for the receiver
- But what is irrelevant to the receiver can only be answered by the receiver, not by the transmitter !?!

Can we play this card forever?

- Better and better codecs are being developed
- Typical compression factors with audio up to 10:1, voice 22:1
- Higher compression comes at more latency !!
- Opposite trend HD (High Definition)
Communications Model
Compression

Identifying more Irrelevance
• What quality level/compression level is appropriate?
• If an artist exercised details for very long, can we simply strip these details off?
• The more detail rich the performance, the less opportunity for compression…
• Is the excellence by an artist simply irrelevant?
• The listeners ear and spectators eye also gets more trained…

By compression the excellence of artist is shaded to the spectators/listeners (and also not captured in archive…)
5. Communication link
There is more than Transinformation with Digital transmission

- Supporting equalization of wireless channel by adding fixed trainings sequences
- Addition of synchronisation information
- Channel coding to make transmission more robust, increasing data
- Σ Overhead by digital transmission

*First we squeeze transinformation by source coding, then we blow it up again*
Communication link
Digital versus Analogue transmission

Common misunderstanding
• Digital is better! – wrong - It can be better, but it also can be worse
• Digital just allows for scalable quality

Digital transmission
• First we apply source coding - we squeeze information, we compress maximal
• Than we blow up by putting on top channel coding to protect data
• We pay a further price by signalling overhead (protocol, training symbols)
Impact of coding languages

- Programming language implies a lot of overhead
- This is waste of spectrum!

- Binär
- JSON
- XML
- Java


When have you downloaded an App last?
Impact of control stack

- Example VoIP (Voice over IP)
- VoIP = raw voice data x33

Factor 33 signalling overhead! - What a waste of spectrum…
6. Spectral Efficiency – what is it?
The spectrum paradox:

Spectrum is a scarce resource, but it is ever underutilized
Spectral Efficiency – what is it?
What do we really want to optimize?

Spectral efficiency of a point to point connection
- Number of bits transported within a second and within a given bandwidth
- Measured as: bit/s/Hz
- Increase by:
  - Better Channel codes
  - High order modulation e.g. 256 QAM
  - MIMO multi antenna systems

Spectral efficiency of a wireless communication system
- Number of bits transported within a second and within a given bandwidth summed over all users normalized to area
- Measured as: bit/s/Hz/km² (aggregated over all users)
- Increase by:
  - Smaller cells, more dense placing of basestations
  - MIMO multi antenna systems

Efficiency of spectrum use, sometimes also called short “spectral efficiency”
- Number of bits totally transported within a second and within a given bandwidth summed over all users normalized to area
- Measured as: bit/s/Hz/km² (aggregated over all users and systems)
- Increase by:
  - Implementation of co-primary and secondary systems, that make use of resources actually not in use by primary systems, opportunistic access, LSA, LAA, CR

IRT Colloquium, Munich, 16. Oct 2017  
Source: Prof. Jondral, KIT
Spectral Efficiency – what is it?
Shannon Law

**Shannon bound**
- This is a fundamental bound we cannot beat

\[ C = BW \cdot \log\left(1 + \frac{S}{N}\right) \]

- **Capacity** [bit/s]
- **Datarate** [bit/s]
- **Bandwidth** [Hz]
- **Signal to Noise Ratio**
  - convert from [dB]

Claude Shannon 1916-2001
Famous researcher in Bell Labs
Founder of information theory


Don’t call a datarate bandwidth !!

Source: Prof. Jondral, KIT
Spectral Efficiency – what is it?
TV Channel 8 MHz

The Low SNR regime pays off better

Low SNR operation is spectrally more efficient!
Spectral Efficiency – what is it?
Don’t be cheated!

Who is more spectrally efficient
old style analogue PMSE  or  advanced digital Cellular?

Source: Benedikt & Jakob
Spectral Efficiency – what is it?
Comparison PMSE versus Cellular

<table>
<thead>
<tr>
<th></th>
<th>PMSE</th>
<th>Cellular / UMTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio Quality</td>
<td>High for content production</td>
<td>Only speech</td>
</tr>
<tr>
<td>Audio rate</td>
<td>CD: 44 kSa/s, 16 bit 704 kbit/s</td>
<td>8 kSa/s, 13 bit (EFR-codec) 104 kbit/s</td>
</tr>
<tr>
<td>Compression</td>
<td>Analogue compander 2:1</td>
<td>Digital source coding 9:1 (22:1 with AMR)</td>
</tr>
<tr>
<td>Compressed Audio rate</td>
<td>352 kbit/s</td>
<td>12 kbit/s</td>
</tr>
<tr>
<td>Channel arrangements</td>
<td>15 channels in 20 MHz</td>
<td>75 channels in 5 MHz</td>
</tr>
<tr>
<td>Raw Audio data related spectral efficiency</td>
<td>0.5 bit/s/Hz</td>
<td>1.56 bit/s/Hz</td>
</tr>
<tr>
<td>Compressed Audio data related spectral efficiency</td>
<td>0.25 bit/s/Hz</td>
<td>0.18 bit/s/Hz</td>
</tr>
</tbody>
</table>

Findings
- Today’s analogue PMSE slightly more spectrally efficient than digital cellular
- Reason, too much signalling overhead in cellular
Spectral Efficiency – what is it?
Comparison PMSE versus Cellular

Sensor, Information Source

Source coding Compression

n:1

Channel Coding Protection

Radio Modem Modulation

Antenna

Spectrum Occupancy

raw data

compressed data

Spectral efficiency
• Do we reference spectrum occupancy to raw sensor data rate or to compressed data?

An experiment of thought
• We take a higher resolution sensor and apply larger compression so that we end up with the same compressed data rate after source coder
• Is this a “spectral efficiency” increase? In View of Shannon not…
• It is an increase in “efficiency of spectrum use”
7. Spectral Efficiency - How to raise it?
Spectral Efficiency - How to raise it?
Generalized view

The Low SNR regime pays off better
Implementation limits spectral efficiency

SNR Range 0...15 dB is efficient
Spectral efficiency barely can get better than 10 for SISO
Historic Capacity Gains in Wireless Networks

Wireless Network Capacity Gains 1950-2000

- 15x by using more spectrum (3 GHz vs 150 Mhz)
- 5x from better voice coding
- 5x from better MAC and modulation methods
- 2700x from smaller cells

Total gain 1 million fold


Network densification has the highest potential, far more than more spectrum (e.g. digital dividend), consequence?
Spectral Efficiency – what is it?
Shannon Law 2.0

Shannon bound 2.0
• Expansion by MIMO
• N TX and M RX antennas

Dimensionality
Number of radio channel Eigenmodes
Best case: L=min{N,M}

\[ C = D \cdot BW \cdot ld \left( 1 + \frac{S}{N} \right) \]

[bit/s] [−] [Hz]

convert from [dB]

We can stretch Shannon by number of radio channel Eigenmodes!
Companies offering IA (Intelligent Antenna, MIMO, Beamforming) solutions fail as spectrum is cheaper than IA…
Spectral Efficiency - How to raise it?
Why did Intelligent Antenna Solutions fail?

Upgrade Scenario
• Upgrade from 1 antenna TX to 4 antennas TX per sector with a basestation
• Intelligent Antenna (beamforming/MIMO)
• Can you get 4x the capacity?
• Theoretically yes! - But practically only on average 2.5 Eigenmodes

Analysis
• 2.5x the capacity for 4x the RF effort – a bad deal
• There is no attractive reward
• Invest in spectrum looks more attractive than invest in IA/MIMO

Reaction
• Complain about spectrum shortage
• MIMO/IA would be more costly
• Network densification also would be more expensive, costly backhauling
• More spectrum is the easiest and lowest cost way
Spectral Efficiency - How to raise it?
Evolution of Cellular

Transition from 3G UMTS to 4G LTE
• Claims x 2.2…2.4 improvement in spectral efficiency (SRD)
• We use turbo codes since UMTS, close to Shannon bound
• Gain is coming mainly from 2x2 MIMO
  (2 Antennas at basestation and 2 and terminal)
• Net Gain by transition from UMTS to LTE x1.1…1.2 → so +10…+20%, what an effort...

Lesson learnt
• Coding research has done excellent work – we reached already the Shannon bound
• There is no revolution to come in transmission
• Channel coding research now mainly for low latency (URLLC)
• Spectral efficiency cannot be increased further
• Only source coding efficiency can be improved

The only remaining option is MIMO and efficient spectrum management (CR, LSA, LAA). This increases efficiency of spectrum use
8. Conclusions
Da steh ich nun, ich armer Tor, und bin so klug als wie zuvor.

Source: Goethe's Faust
Conclusions
Lessons learnt

Growth laws
• Microelectronics integration density doubles every two years
• Production and distribution demands grow both and fast

Separation theorem
• Under no latency constraints, source coding and channel coding can be treated independently

Shannon law
• Only covers channel coding and modulation, valid only for infinite block length
• For low latency transmission easily a hit by 10 dB

Spectral efficiency
• Spectrum occupancy referenced to data after source coding
• Thus independent of sensor source and source coding
• Covers channel coding and modulation
• Low SNR regime 0…15 dB advisable, SE barely can get better than 10 due to Implementation

Way out?
• MIMO, Dynamic spectrum management (Spectrum Sharing, CR, LAA, LSA)
• Increase efficiency of spectrum use!
Conclusions
Why we need more capacity on production and distribution

Artist
• Multiple units on actor’s body
• Latency Roundtrip 3…5 ms

PMSE is challenging
• HD Multimedia wireless
• Immersive Sound and Video
• Effect control

Photo: ZDF (D)