TECHNISCHE UNIVERSITÄT DRESDEN

Vodafone Chair Mobile Communications Systems, Prof. Dr.-Ing. Dr. h.c. G. Fettweis

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The Limits of 4G and How to Design a New 5G PHY

Gerhard P. Fettweis – Vodafone Chair Professor

CTW 2013

25th June 2013, Phuket

vodafone chair at TU Dresden

Key Facts and Figures

The Team

- 1 professor
- 8 senior scientists/lecturers/post-docs
- 32 Ph.D. students
- 15+ Master students
- 4 program managers
- 8 start-up incubator employees
- 5 secretaries
- 5 lab engineers

IPP Sponsors

actix, ALTERA, Alcatel·Lucent, AsahiKASEI, BOSCH, HUAWEI, Intel Mobile Communications, NATIONAL INSTRUMENTS, Nokia Siemens Networks, ROHDE&SCHWARZ, SIGNALION, tensilica, SYNOPSYS, XILINX

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Accomplishments

Scientific:

- 62 Ph.D. grads
- 200+ Ms. grads
- 700+ publications
- 9,000+ citations
- 200+ patent appl.
- 85+ patent families

Innovation:

- 10 spin-outs
- 350 engineers

Funding:

- € 50M Chair
- € 50M VC
- € 1/3B projects

Project Partners

NATIONAL INSTRUMENTS, vodafone, GWT forschung + innovation, actix, Alcatel·Lucent, BT, Fraunhofer Heinrich Hertz Institute, NEC, SAGEMCOM, ST ERICSSON, 7 2007 - 2013, Deutsche Forschungsgemeinschaft DFG, Bundesministerium für Bildung und Forschung, Freistaat Sachsen Staatsministerium für Wissenschaft und Kunst

The Vodafone Chair's Startup History

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Startup	Acquired	Acquired by	founded
systemonic	2002	NXP founded by Philips	1999 OnDSP™ based WLAN chip-sets
radioplan	2006	actix	2000 SON systems
SIGNALION	2012	NATIONAL INSTRUMENTS	2003 Broadband Wireless HW (LTE,…)
IN-CIRCUIT	2006	IN-CIRCUIT	2004 Module and reference board design
DRESDEN SILICON	2007	SIGNALION	2005 MPSoC semiconductor IP
freedelity			2007 Wireless audio
RADIOOPT			2008 Network performance measurement
blue wonder communications	2010	intel	2008 LTE Cellular Handset Chip IP
INRADIOS integrated radio solutions			2010 Satellite Communications
exelonix			2013 Assisted living
STARTBAHN Venture Fonds			2012 Startbahn Venture Fund

5G – What Is It?

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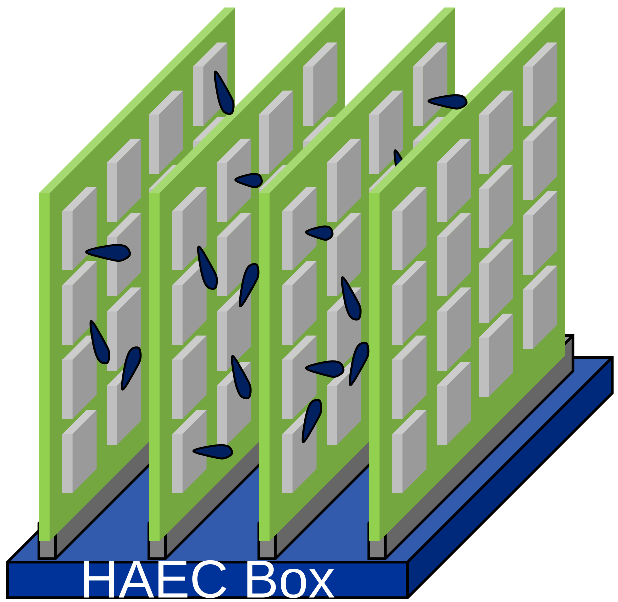
WIRELESS ROADMAP

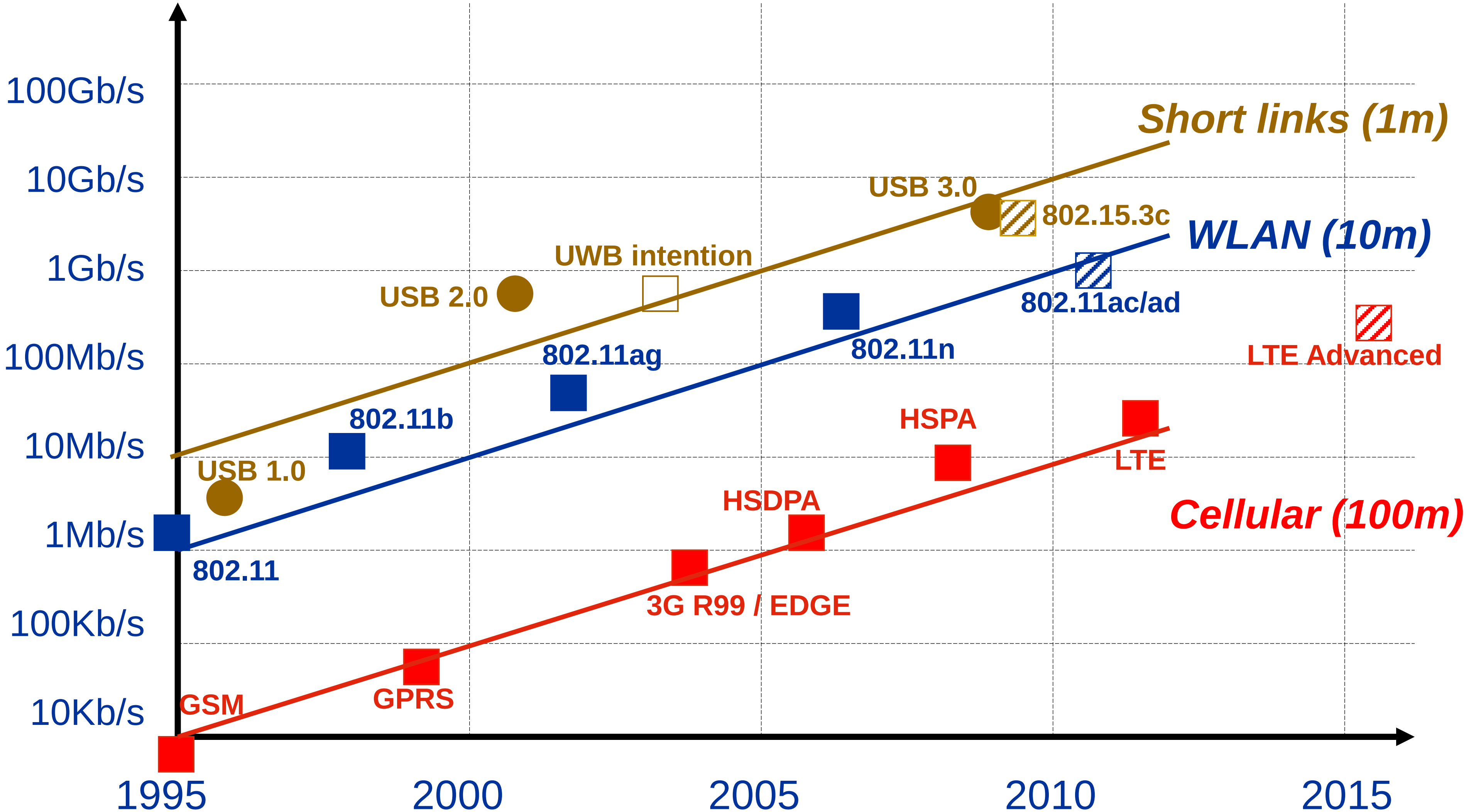
The Outlook: The HAEC Box in 2020+

Assume	128K processors per chip	4x4 chip-stacks on board
	128x chips stacked in 3D	4x boards in a box



in 10x10x10 cm^3 (1 liter)	→ 10^9 processors!
8192 chips	→ 10^5x performance of today!

Coverage: Cellular



>2020 Outlook

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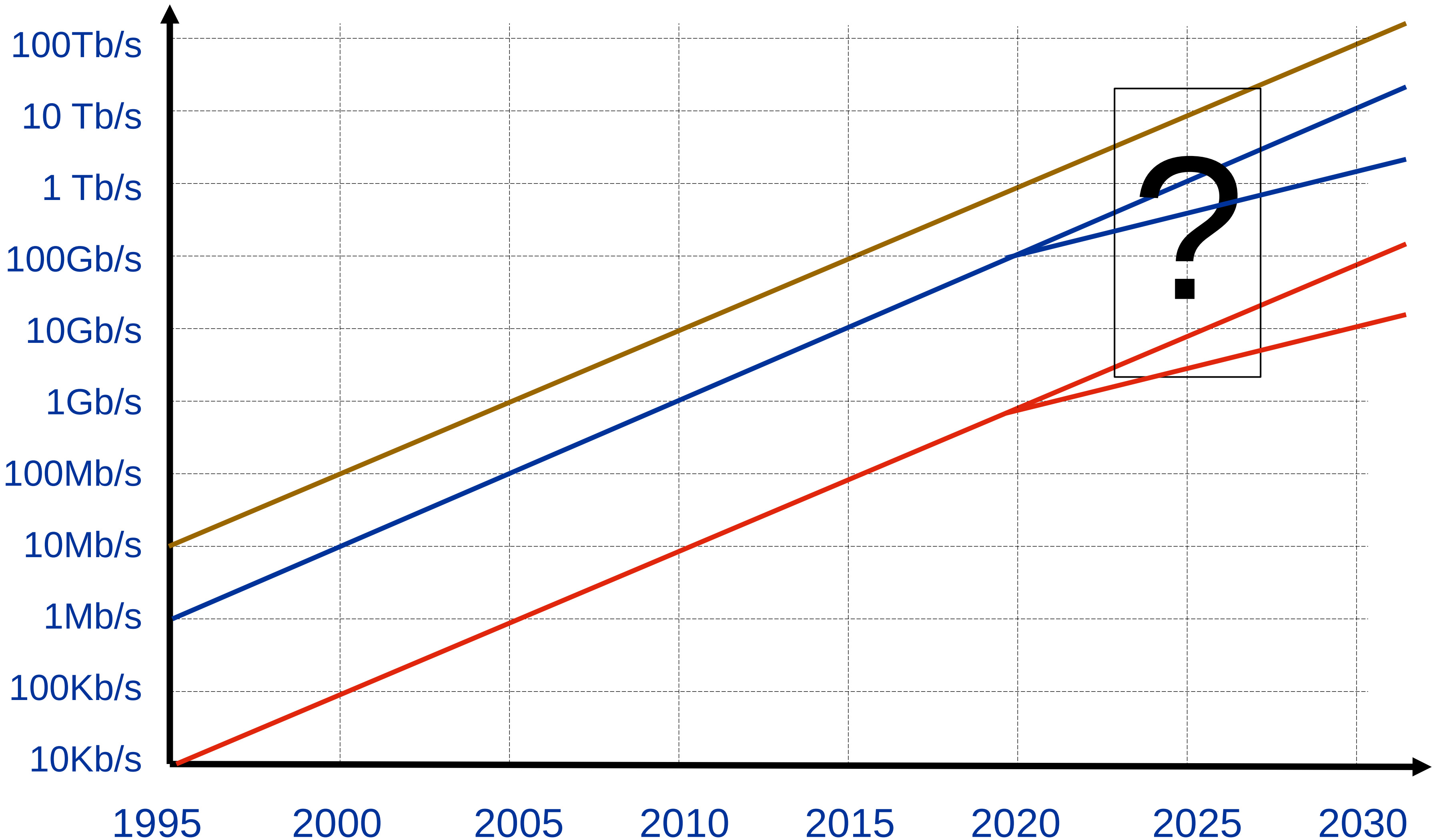

2005/4/4 – Via Della Conciliazione

Source: http://www.spiegel.de/panorama/bild-889031-473266.html

2013/3/12 – Via Della Conciliazione

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Enabling Ad-Hoc Mobile “Free-Viewpoint Video”

Source: http://www.spiegel.de/panorama/bild-889031-473242.html

Watch Out !

http://static.o2.co.uk/www/img/iphone-device/4_phones.png
http://www.iclarified.com/images/news/28607/111946/111946-1280.png

5G

THE TACTILE INTERNET

G. Fettweis

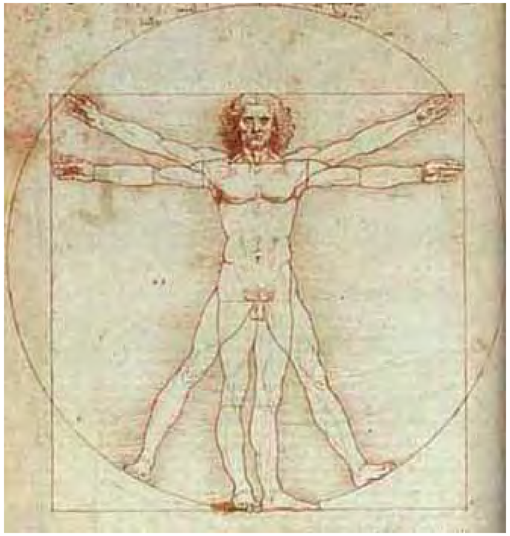
A 5G Wireless Communications Vision , 2012-12-15, Microwave Journal

www.microwav ejournal.com/articles/print/18751-a-5g-wireless-communications-v ision

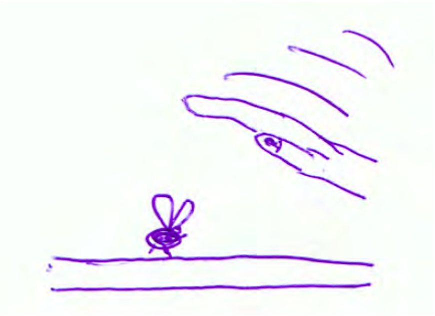
Human Reaction – How Fast is Fast?

http://i.cdn.turner.com/si/multimedia/photo_gallery/1108/famous.false.starts/images/01.bolt.jpg

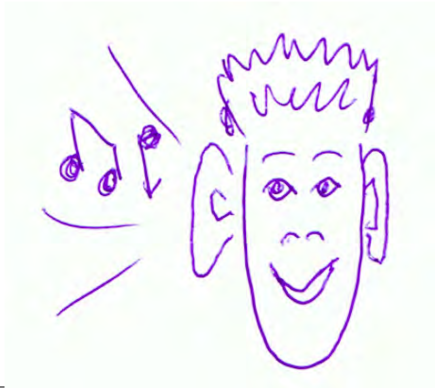
Physiology and Psychology



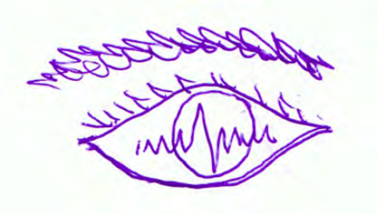
1 sec



100ms

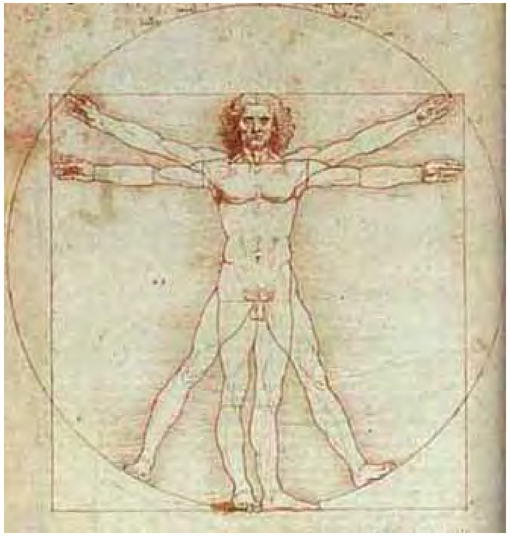


10ms

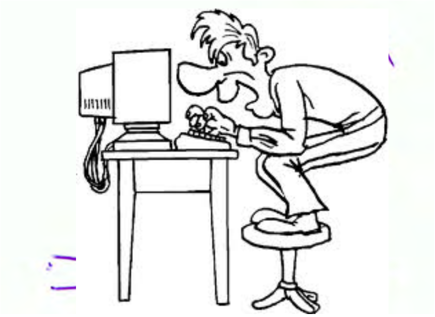


1ms

Physiology and Psychology



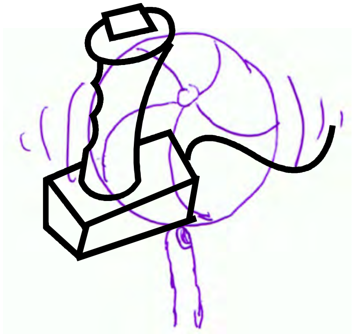
1 sec



100ms

10ms

1ms



Gaming…

http://popular-pics.com/Cool_World_Record_LAN_Event_Computer_Pictures__5
http://gametaffy.com/imho-the-lan-party/

Professional Audio

http://www.germanpulse.com/wp-content/uploads/2013/02/HerbertGroenemeyerGuitarPhotoByAliKepenek.jpg

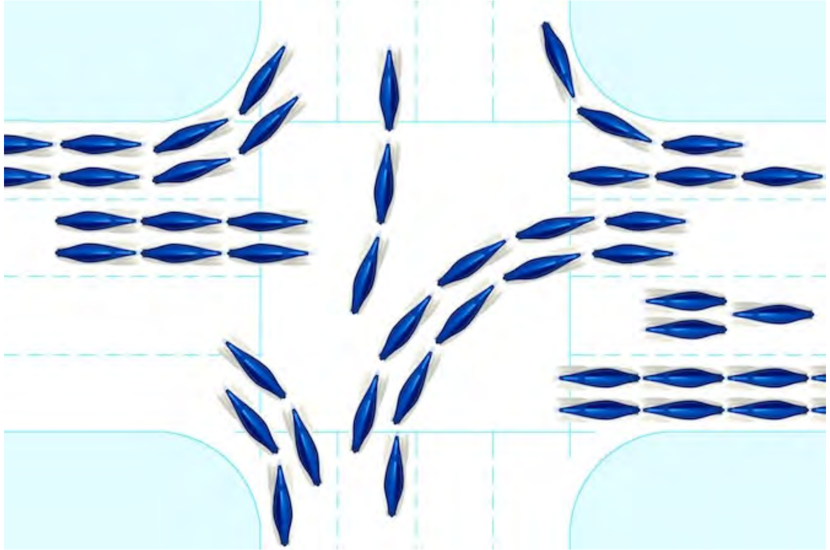
Remote Heli

http://ds_product_photos.s3.amazonaws.com/large/9756.jpg

- Today's urban Traffic

Example: Urban Traffic at Arc de Triomphe

- Future Vision



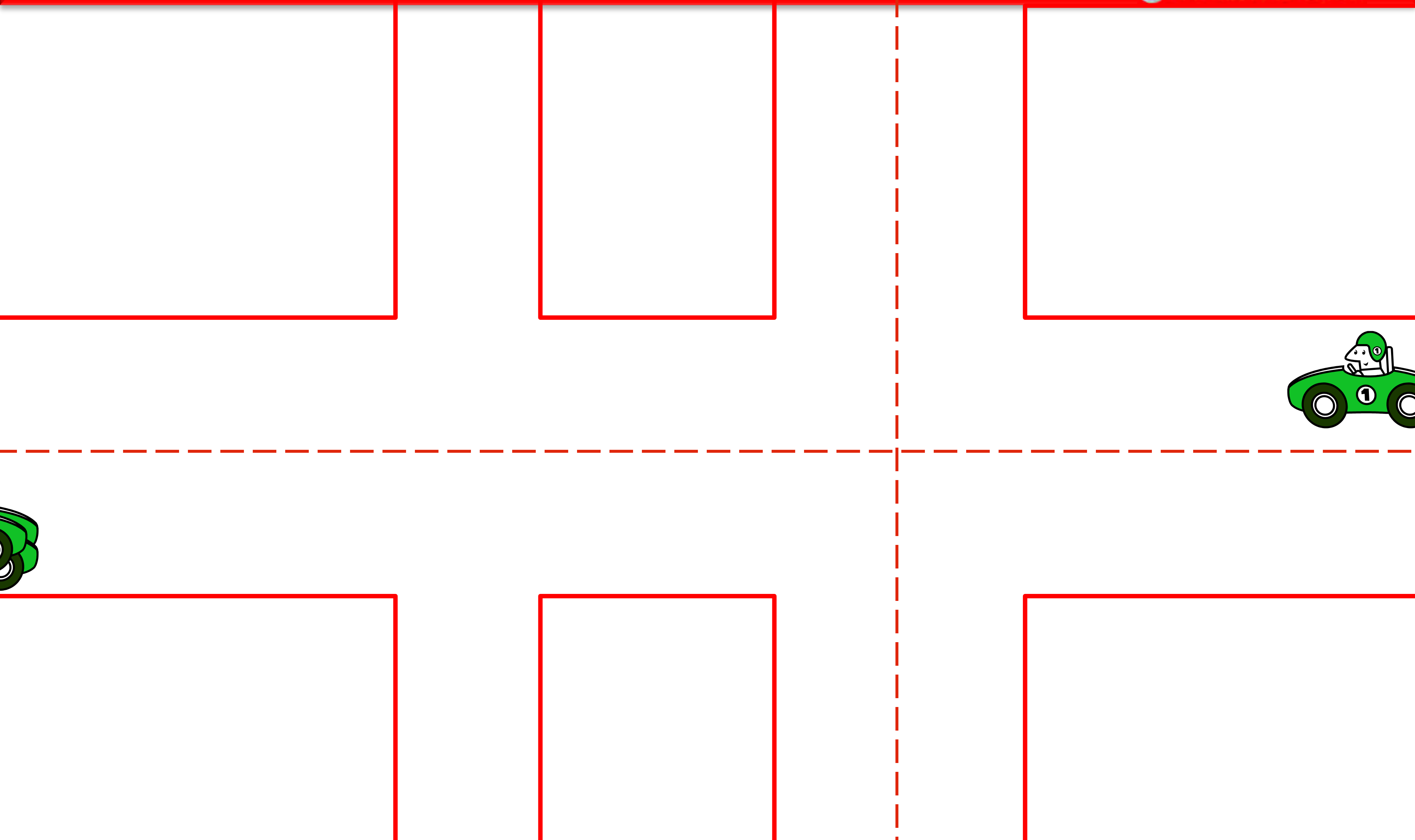
Remote Driving 2.0

Platooning 2.0

- 1ms examples of today's cars: ESP, ABS

- Tomorrow: platooned ESP & ABS

Traffic Control



Wireless Airbags

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Crash to impact: 10-15ms

- Crash sensor
- Trigger
- Air bag

Exoskeletons – “Power Limbs”

http://news.cnet.com/8301-17938_105-57532729-1/nasa-exoskeleton-suit-is-half-way-to-iron-man/

Health / Physiotherapy

http://www.medindia.net/patients/patientinfo/images/physiotherapy.jpg

Manufacturing

http://www.augsburg.de/fileadmin/www/dat/fotoservice/wirtschaft/kuka/kuka_1.jpg

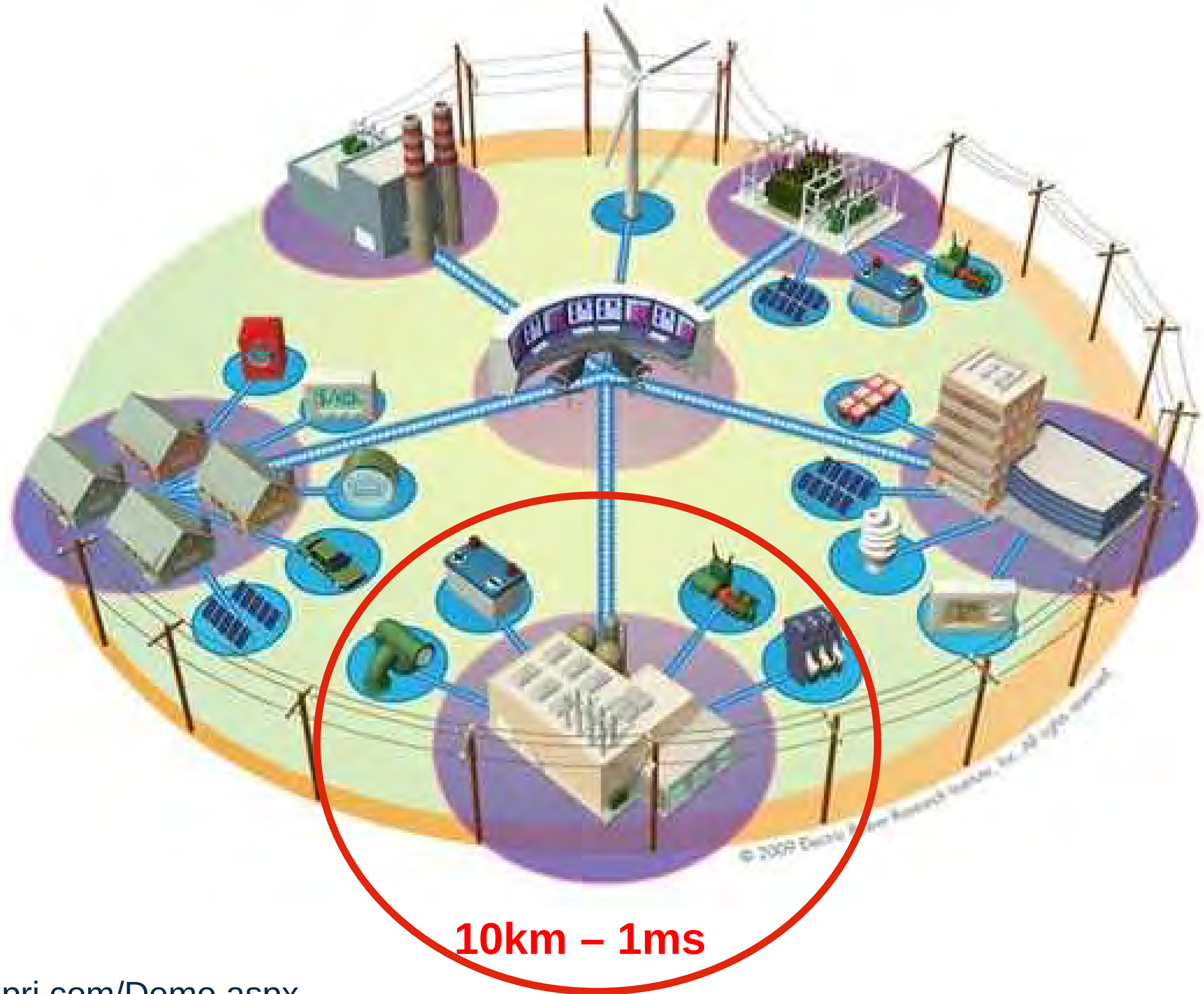
Sports

http://www.spox.com/de/sport/olympia/0807/Artikel/Terminplaene/zeitplan-kanu.html

Virtual Overlay

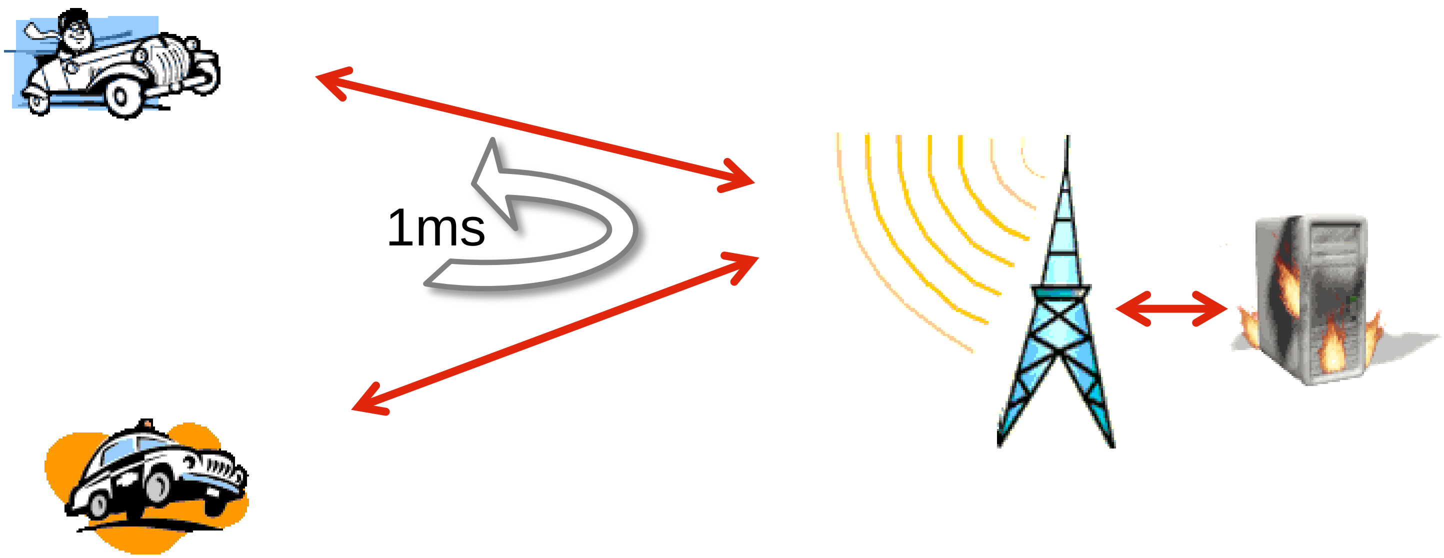
http://googlesystem.blogspot.de/2009/12/google-goggles-mobile-visual-search.html

Smart Grid



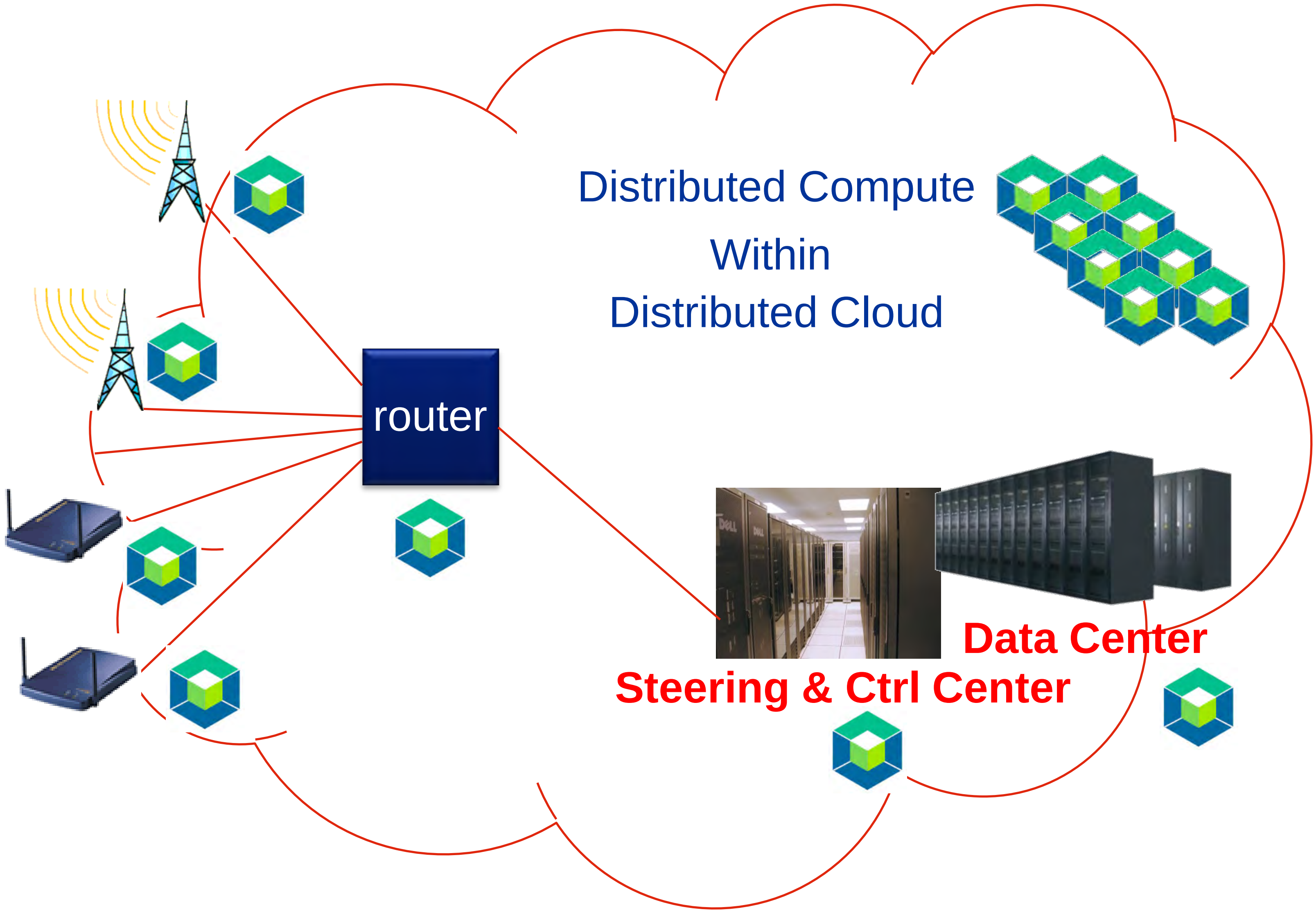
http://smartgrid.epri.com/Demo.aspx

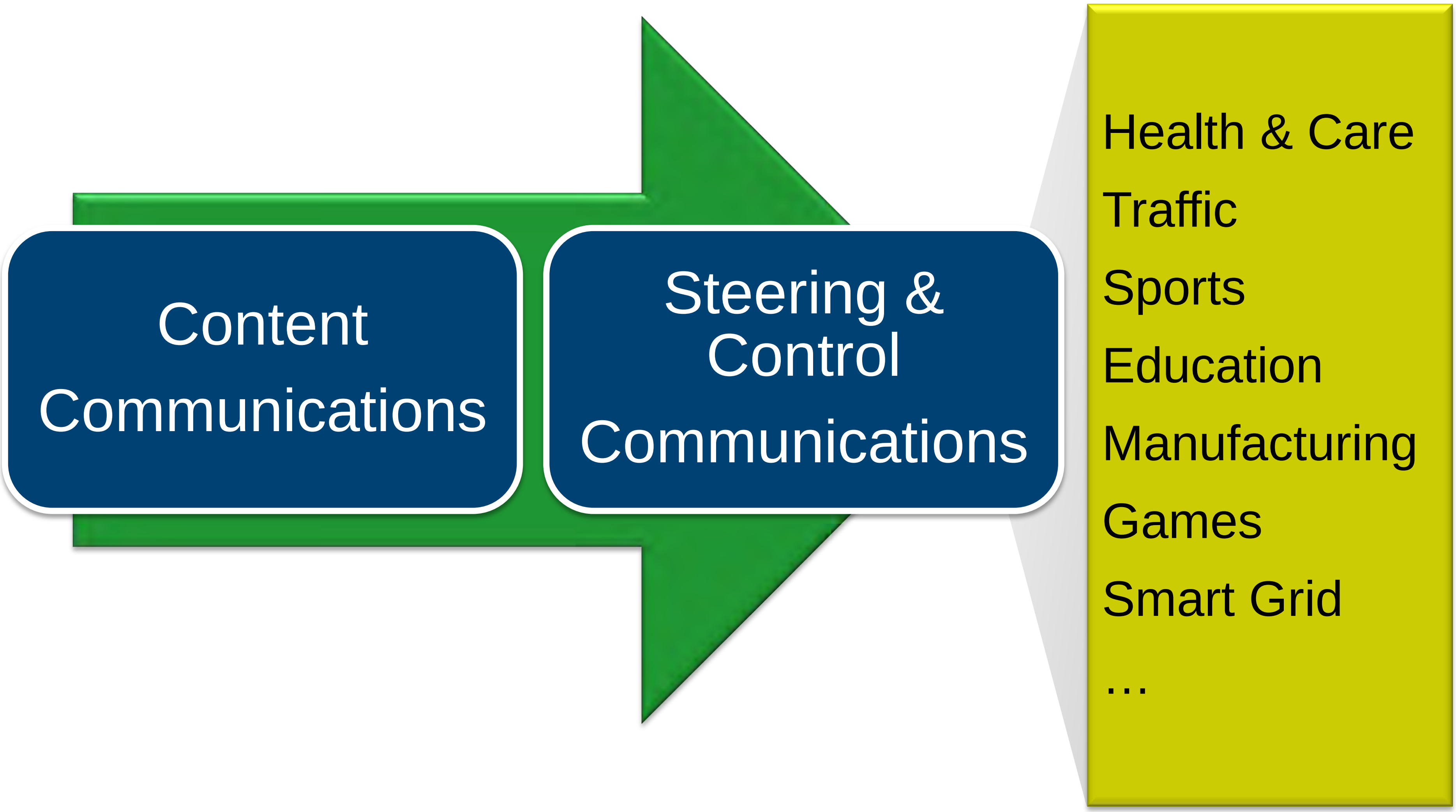
Paradigm of 5G Cellular: Control



Traffic / Sports / Education / Health&Care / Manufacturing / Games / Smart Grid…

SmartRAN


Distributed Compute
Within
Distributed Cloud
router
Data Center
Steering & Ctrl Center


Content Communications
Steering & Control Communications
Health & Care
Traffic
Sports
Education
Manufacturing
Games
Smart Grid
…

For more on “Tactile Internet”

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Youtube: “**Tactile Internet Gerhard**”

http://www.youtube.com/watch?v=_VXEPzQgpok

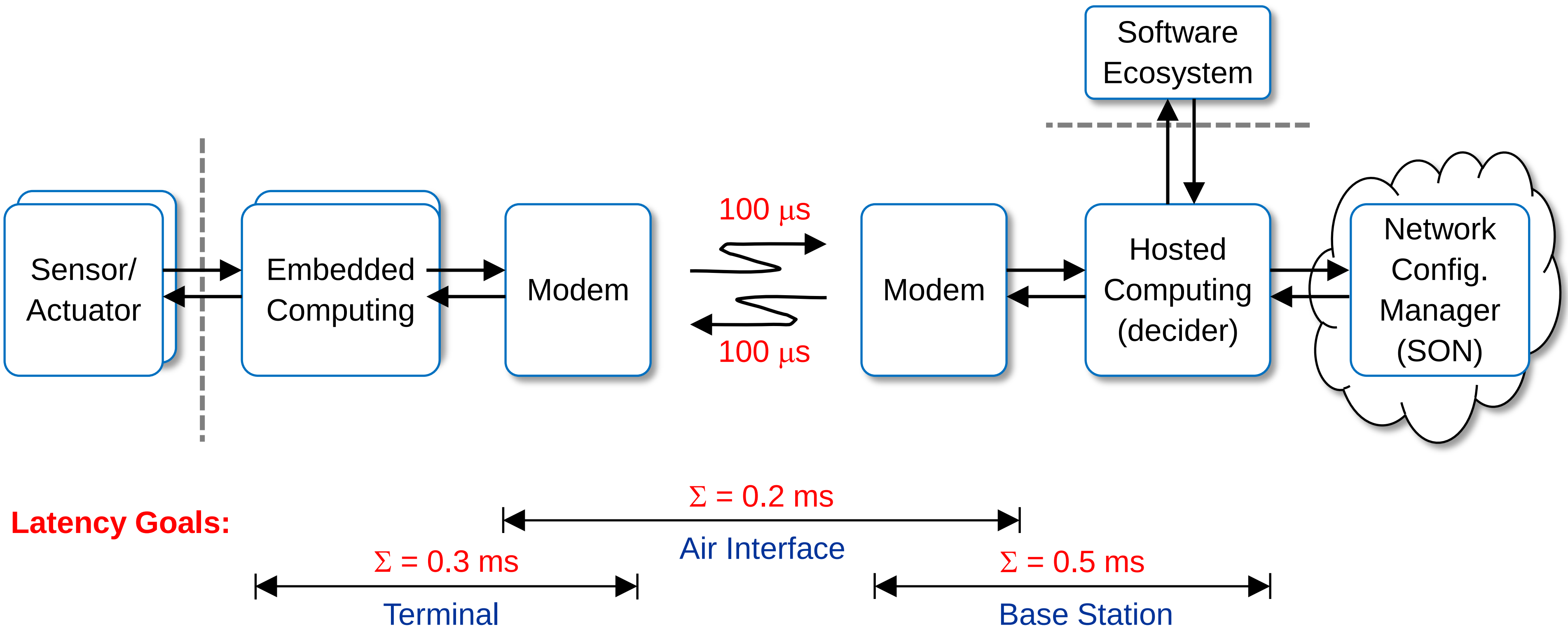
Microwave Journal Dec/2012 feature article on 5G

G. Fettweis

A 5G Wireless Communications Vision , 2012-12-15, Microwave Journal

www.microwavejournal.com/articles/print/18751-a-5g-wireless-communications-vision

10ms ➔ 1ms Impact: 32μs Packet



5G

WHICH MODULATION?

Background

Speed of light

$$c = 300km/ms$$

GSM: one GMSK symbol

$$3.7\mu s \triangleq 1100m$$

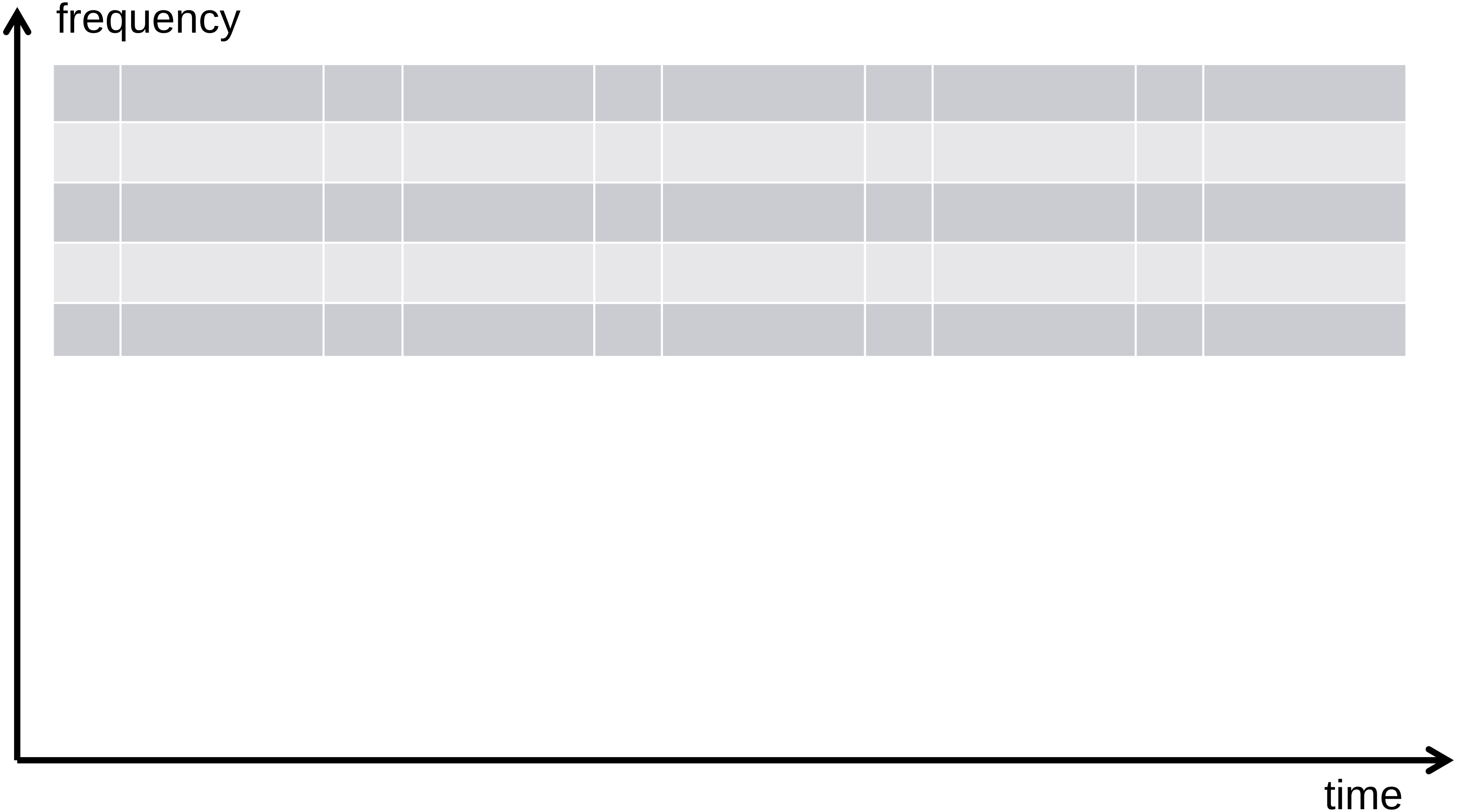
3G: one DS-CDMA chip

$$0.26\mu s \triangleq 78m$$

LTE: one OFDM symbol

$$70\mu s \triangleq 21km$$

Time-Frequency Grid of OFDM



OFDMA

OFDMA Highlights

- Variable channel bandwidth
- Scheduling & RRM
- Low complexity in signal processing

Limitations of OFDMA

- Frequency synchronous operation
  and limits on phase noise
- Spectrum shaping:
  spectrum mask, spectrum aggregation, and ACLR
- Symbol design limitations:
  Subcarrier spacing / symbol duration
- ASA (Authorized Shared Access): Carrier sensing

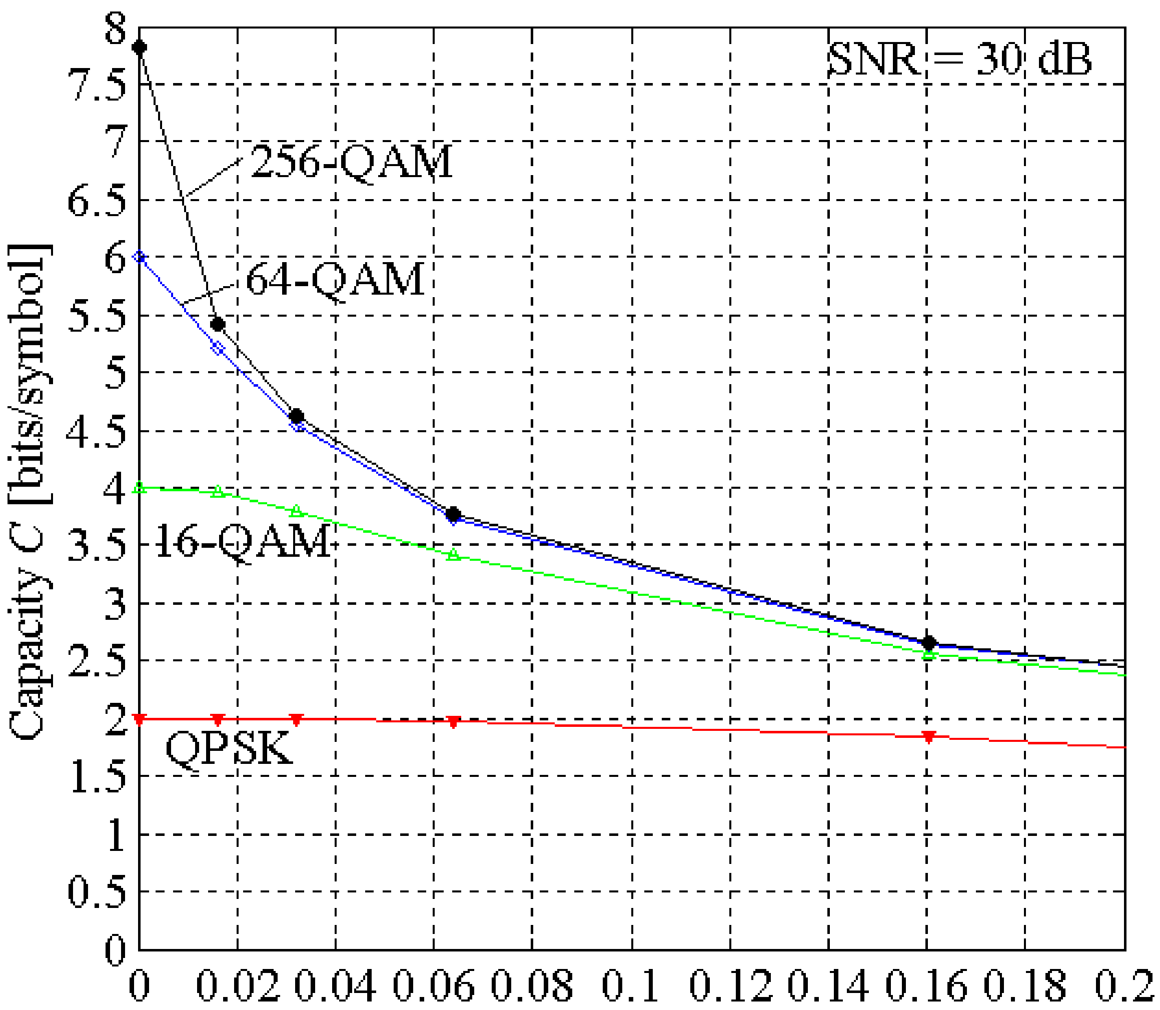
Packet/Symbol Duration for 5G

$$\Delta f_{sub} = 1/T_{symbol}$$

A packet T_{packet} (TTI) of max. 32µs and at least 10 symbols:

$$\Delta f_{sub} \geq \frac{10}{T_{packet}} = \frac{1}{T_{symbol}} = 312.5kHz$$

OFDM: Phase Noise Impairing Capacity



$\Delta f_{3dB} / \Delta f_{sub}$

Δf_{sub} sub-carrier spacing

Doppler Spread (1)

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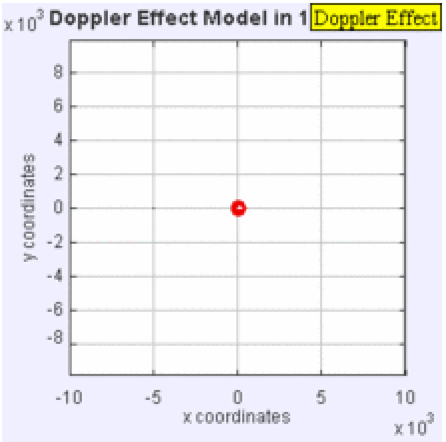
$$B_d \cong 2 \frac{v}{\left[\frac{km}{h}\right]} \frac{f_c}{[GHz]}$$



http://upload.wikimedia.org/wikipedia/commons/thumb/c/c9/Dopplereffectsourcemovingrightatmach0.7.gif/220px-Dopplereffectsourcemovingrightatmach0.7.gif

4GHz carrier and 250km/h ➔ 2kHz Doppler Spread!

$$\Delta f_{sub} \geq 200kHz$$

Doppler Spread (2)

2kHz Doppler Spread:

➔ approx. 500μs coherence time

➔ CSI update period of 50μs sensible = T_{packet} (TTI) duration

Delay Spread & Coherence Bandwidth

coherence bandwidth ≥ 10x subcarrier spacing

$$B_c \geq 10 * \Delta f_{sub}$$

Assuming 1km “delay spread”

$$f_{sub} \leq \frac{B_c}{10} = \frac{1}{10 * 3\mu s} = 33kHz$$

Summarizing Multicarrier for 5G

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Doppler Spread	$\Delta f_{sub} \geq 200kHz$
Coherence Bandwidth	$\Delta f_{sub} \leq 33kHz$
Coherence Time	$T_{packet} \leq 50\mu s$ $T_{symbol} \leq 5\mu s$ $\Delta f_{sub} \geq 200kHz$
Latency	$\Delta f_{sub} \geq 312.5kHz$ $T_{packet} \leq 32\mu s$

➔ **ISI on subcarriers**

2-Stage Sphere-Detector for SC-FDMA Transmission over MIMO ISI Channel

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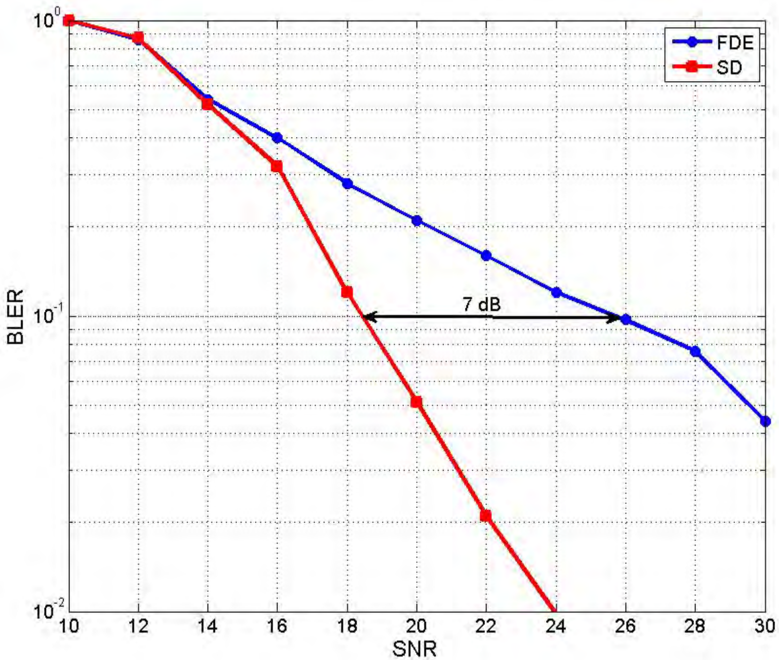
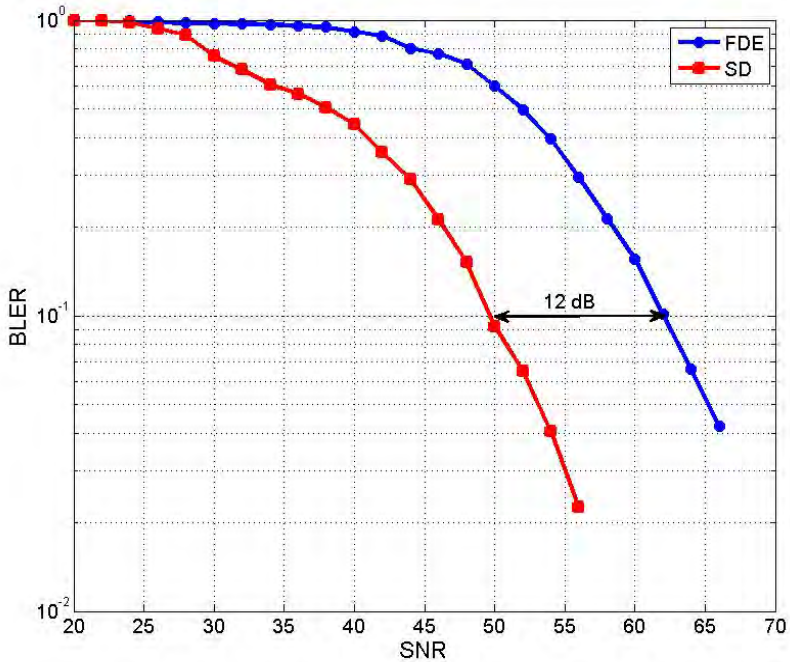
- Correlation between antennas makes performance gain more pronounced
- Scenario: 4x4 MIMO, CQI 10 (64QAM, 0.455 code rate)



Uncorrelated channel

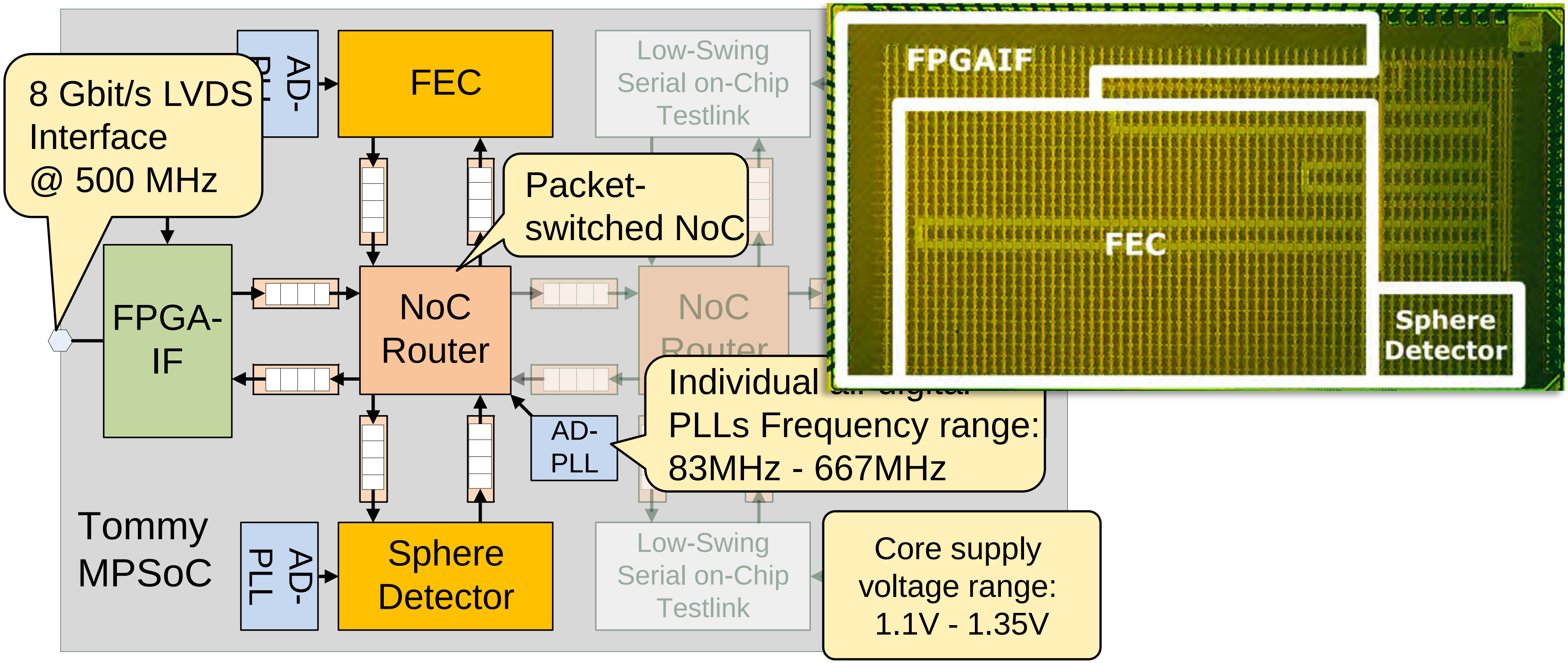


Channel Correlation 0.3

M. Jar, E. Matus, E. Pérez Adeva, E. Ohlmer and G. Fettweis
Two-Stage Detector for SC-FDMA Transmission over MIMO ISI Channels, in *Pro.of 9th International Symposium on Wireless Communication Systems (ISWCS'12)*, Paris, France, 28.8. - 31.8.2012

The „Tommy“ System-on-Chip

- 7.03 mm² die with 17 million transistors (65nm TSMC LP process)
- GALS SoC Approach
- 300Mbps @ 40mW Detection & 370mW Decoding



: M. Winter, S. Kunze, E. Pérez Adeva, B. Mennenga, E. Matus, G. Fettweis, H. Eisenreich, G. Ellguth, S. Höppner, S. Scholze, R. Schüffny and T. Kobori. „A 335Mb/s 3.9mm² 65nm CMOS Flexible MIMO Detection-Decoding Engine Achieving 4G Wireless Data Rates.“ IEEE ISSCC 2012

5G Modulation Requirements

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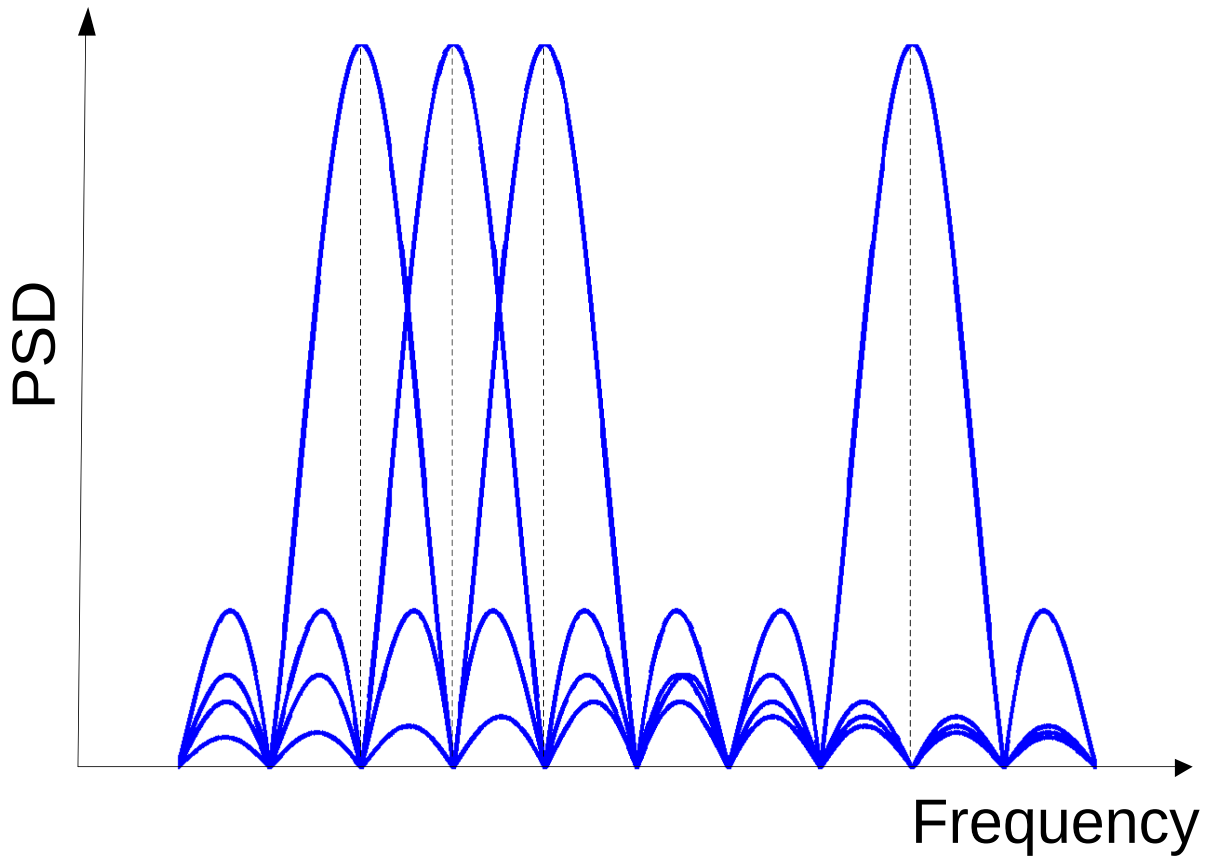
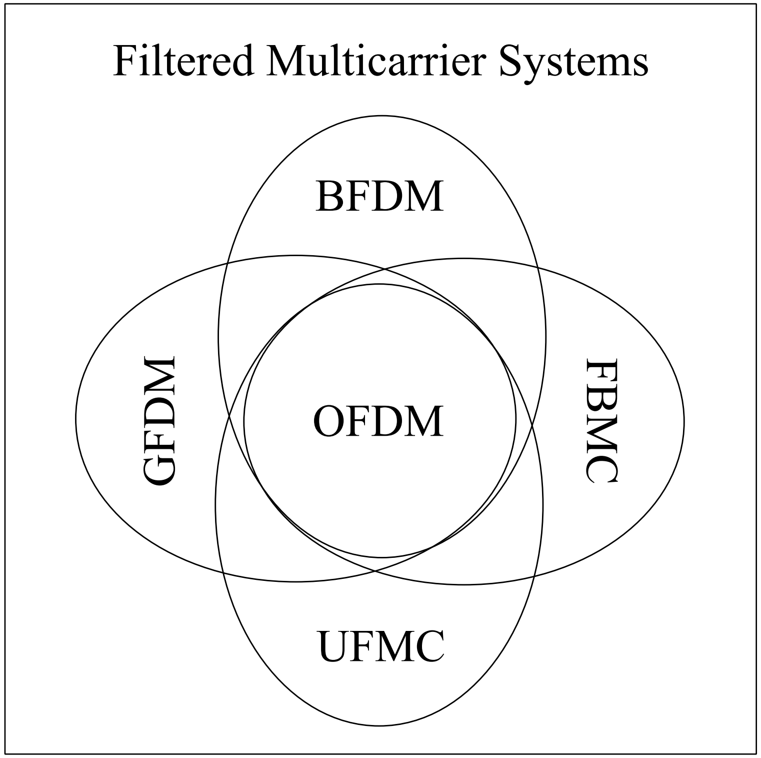
- Multi-Carrier

- Carrier sensing (ASA)
  Low out-of-band radiation (ACLR)
  Non synchronous usage
  (time/frequency multiple access)
  → filtered subcarriers

OFDM(A)



Overview of Multi-Carrier Schemes



OFDM	Orthogonal Frequency Division Multiplexing
BFDM	Biorthogonal Frequency Division Multiplexing
FBMC	Filter Banks Multicarrier
UFMC	Universal Filtered Multicarrier
GFDM	Generalized Frequency Division Multiplexing

GFDM Basic Idea

Generalized Frequency Division Multiplexing

G. Fettweis, M. Krondorf and S. Bittner

GFDM - Generalized Frequency Division Multiplexing

in *Proceedings of the 69th IEEE VTC Spring'09*, Barcelona, Spain, 26.4. - 29.4.2009

I. Gaspar, N. Michailow, A. Navarro, E. Ohlmer, S. Krone, G. Fettweis,

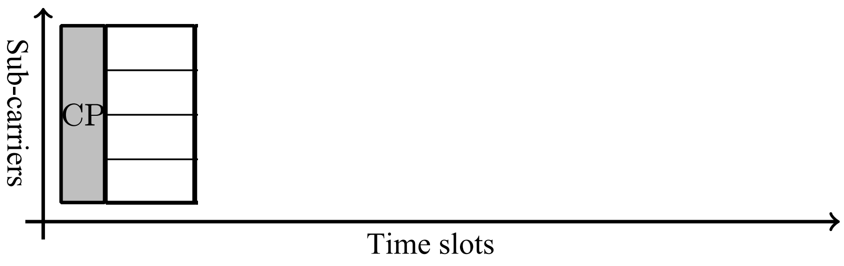
"Low Complexity GFDM Receiver Based On Sparse Frequency Domain Processing,"

In Proc. of VTC Spring 2013, Dresden.

GFDM Signal Properties

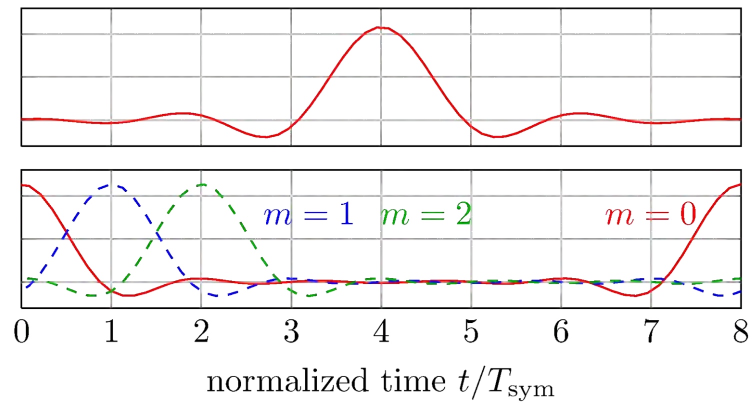
Multi-carrier scheme

Block based approach

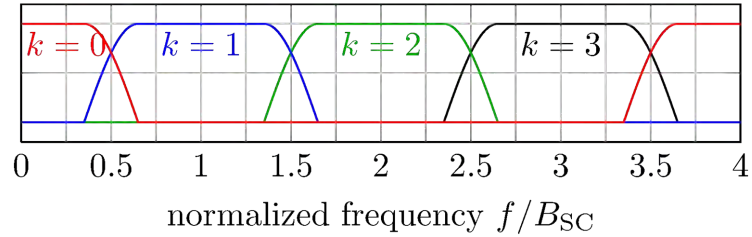


Circular signal structure (time and frequency)

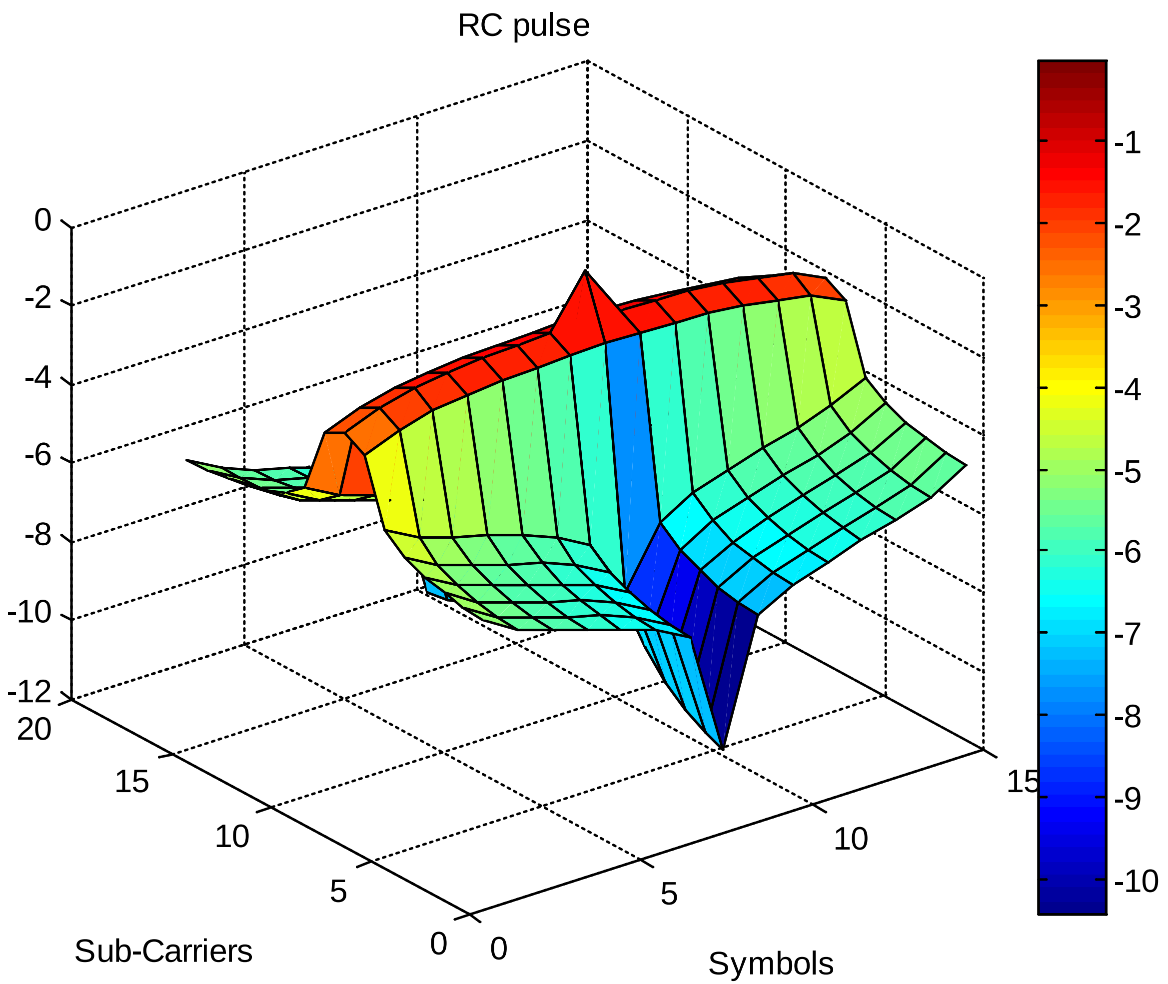
Pulse shaped sub-carriers



Overlapping sub-carriers



Spectral Shaping: E.g. RC



Transmitter Descriptions

Approach 1:

Superposition

$$x[n] = \sum_{k=0}^{N-1} \sum_{m=0}^{M-1} d_{k,m} g[n] \delta[n - mN] e^{-j2\pi \frac{k}{N} n}$$

Approach 2:

Modulation matrix

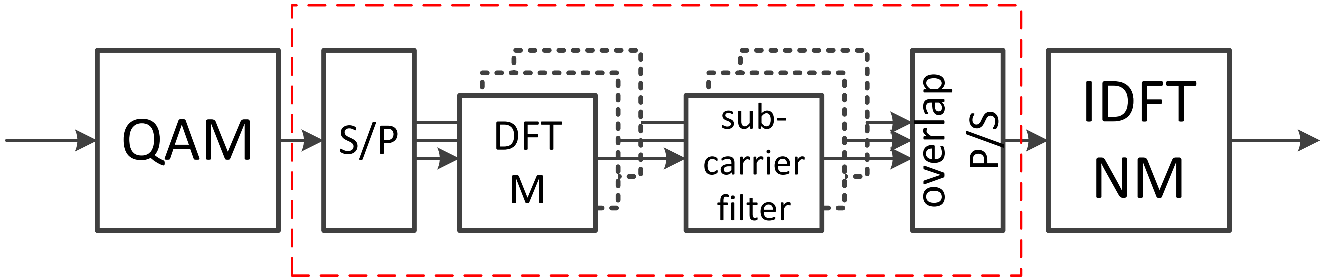
$$\mathbf{x} = \mathbf{A}\mathbf{d}$$

Approach3:

Fourier transform

$$\mathbf{x} = \mathbf{W}_{NM}^{\mathrm{H}} \sum_{k=0}^{K-1} \mathbf{P}^{(k)} \mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} \mathbf{R}^{(L)} \mathbf{W}_M \mathbf{d}_k,$$

Transmitter Description



$$\mathbf{x} = \mathbf{W}_{NM}^{\mathrm{H}} \sum_{k=0}^{K-1} \mathbf{P}^{(k)} \mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} \mathbf{R}^{(L)} \mathbf{W}_M \mathbf{d}_k$$

- $\mathbf{x}$: transmit samples
- $\mathbf{W}_{NM}^{\mathrm{H}}$: transform to time domain
- $\sum_{k=0}^{K-1}$: superposition
- $\mathbf{P}^{(k)}$: permutation = upconversion
- $\mathbf{\Gamma}_{\mathrm{Tx}}^{(L)}$: pulse shaping
- $\mathbf{R}^{(L)}$: repetition = upsampling
- $\mathbf{W}_M$: transform to freq. domain
- $\mathbf{d}_k$: complex data

$$\mathbf{W}_M = \{w_{i,j}\}_{M\times M}, \text{ where } w_{i,j} = e^{-j2\pi\frac{ij}{M}} \text{ with } i,j = 0,\ldots,M-1$$

$$\mathbf{R}^{(L)} = \underbrace{\begin{pmatrix} \mathbf{I}_M & \mathbf{I}_M & \ldots \end{pmatrix}}_{L}^{\mathrm{T}}$$

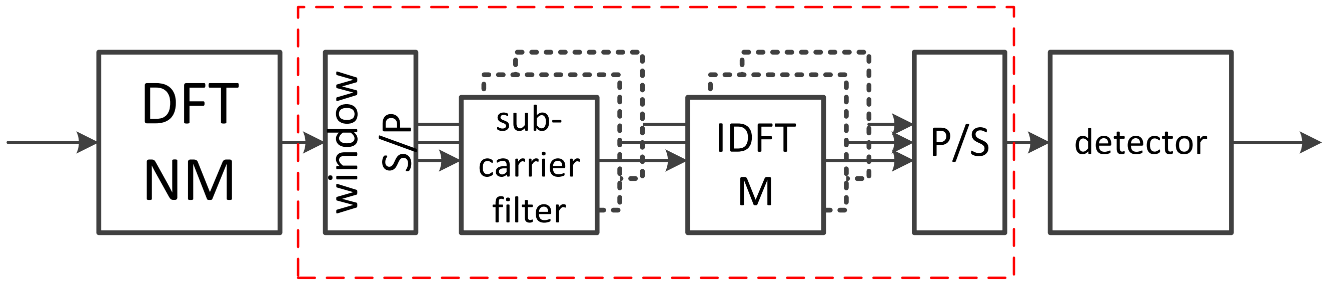
$$\mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} = \mathrm{diag}\left(\mathbf{W}_{LM}\mathbf{g}_{\mathrm{Tx}}^{(L)}\right)$$

$$\mathbf{P}^{(0)} = \begin{pmatrix} \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

$$\mathbf{P}^{(1)} = \begin{pmatrix} \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

k	sub-carrier index
M	number of time slots per block
L	width of the filter (freq. domain)
N	total number of sub-carriers

Receiver Description



$$\hat{\mathbf{d}}_k = \mathbf{W}_M^{\mathrm{H}} \left(\mathbf{R}^{(L)}\right)^{\mathrm{T}} \mathbf{\Gamma}_{\mathrm{Rx}}^{(L)} \left(\mathbf{P}^{(k)}\right)^{\mathrm{T}} \mathbf{W}_{NM}\, \mathbf{y}$$

received data · transform to time domain · decimation = downconversion · receive filter · sub-carrier selection · transform to frequency domain · receive samples

$$\mathbf{W}_M = \{w_{i,j}\}_{M\times M}, \text{ where } w_{i,j} = e^{-j2\pi\frac{ij}{M}}$$
$$\text{with } i,j = 0,\ldots,M-1$$

$$\mathbf{R}^{(L)} = \big(\underbrace{\mathbf{I}_M \;\; \mathbf{I}_M \;\; \ldots}_{L}\big)^{\mathrm{T}}$$

$$\mathbf{\Gamma}_{\mathrm{Tx}}^{(L)} = \operatorname{diag}\left(\mathbf{W}_{LM}\mathbf{g}_{\mathrm{Tx}}^{(L)}\right)$$

$$\mathbf{P}^{(0)} = \begin{pmatrix} \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

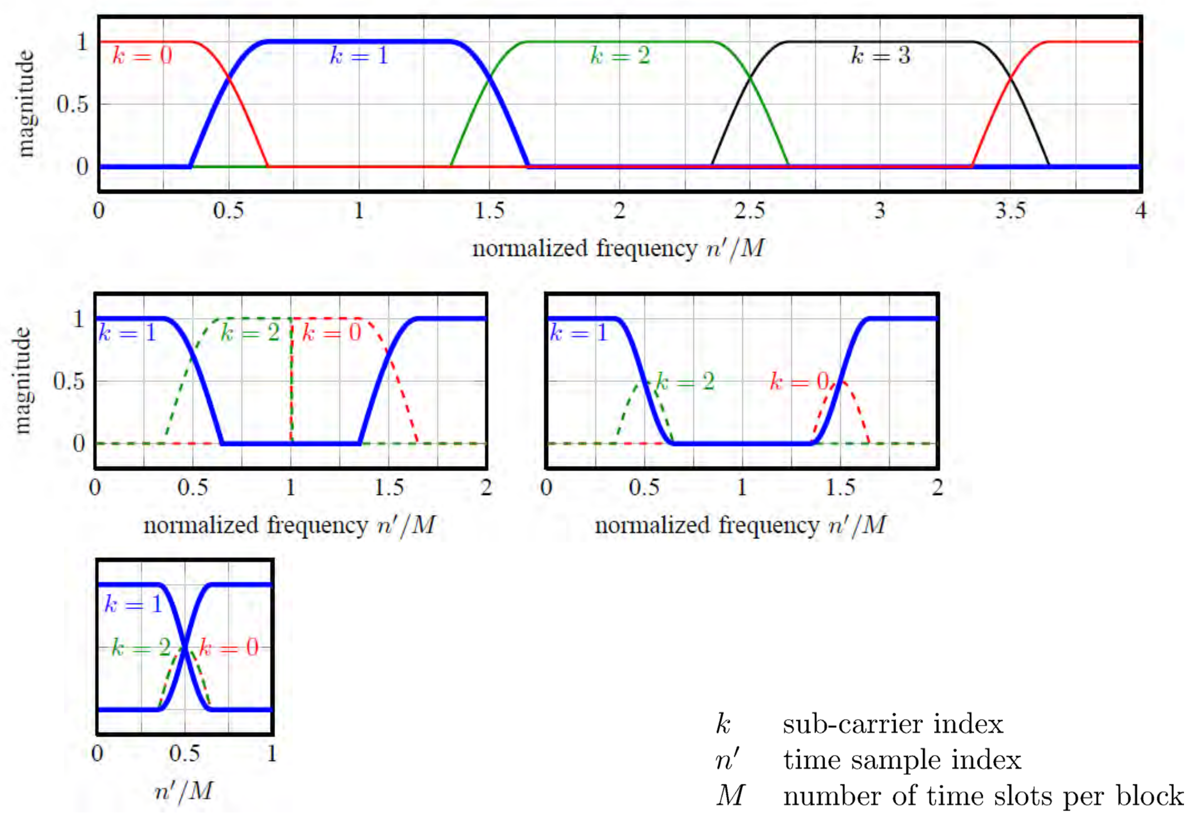
$$\mathbf{P}^{(1)} = \begin{pmatrix} \mathbf{0}_{LM/2} & \mathbf{I}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \\ \mathbf{I}_{LM/2} & \mathbf{0}_{LM/2} & \cdots & \mathbf{0}_{LM/2} & \mathbf{0}_{LM/2} \end{pmatrix}^{\mathrm{T}}$$

k	sub-carrier index
M	number of time slots per block
L	width of the filter (freq. domain)
N	total number of sub-carriers

Low Complexity Transceiver

Performing signal processing in frequency domain allows low complexity version of transmitter and receiver.

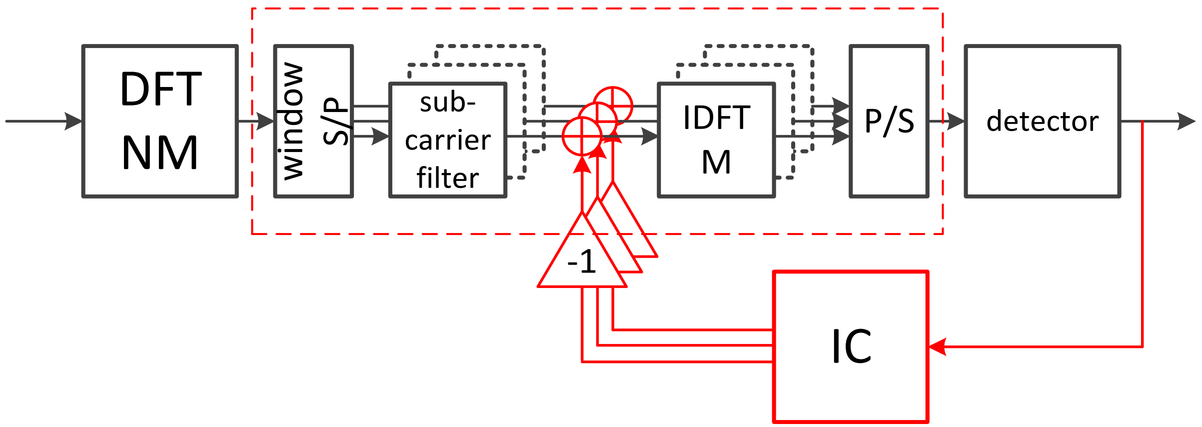
- Pulse shaping filter is sparse in frequency domain
- Convolution becomes multiplication
- Decimation becomes superposition

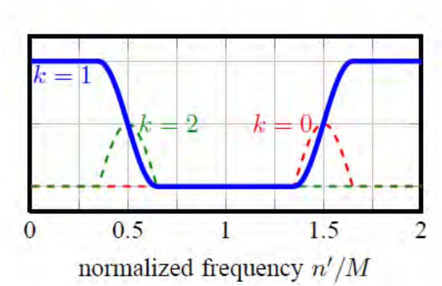


Low Complexity Transceiver (2)

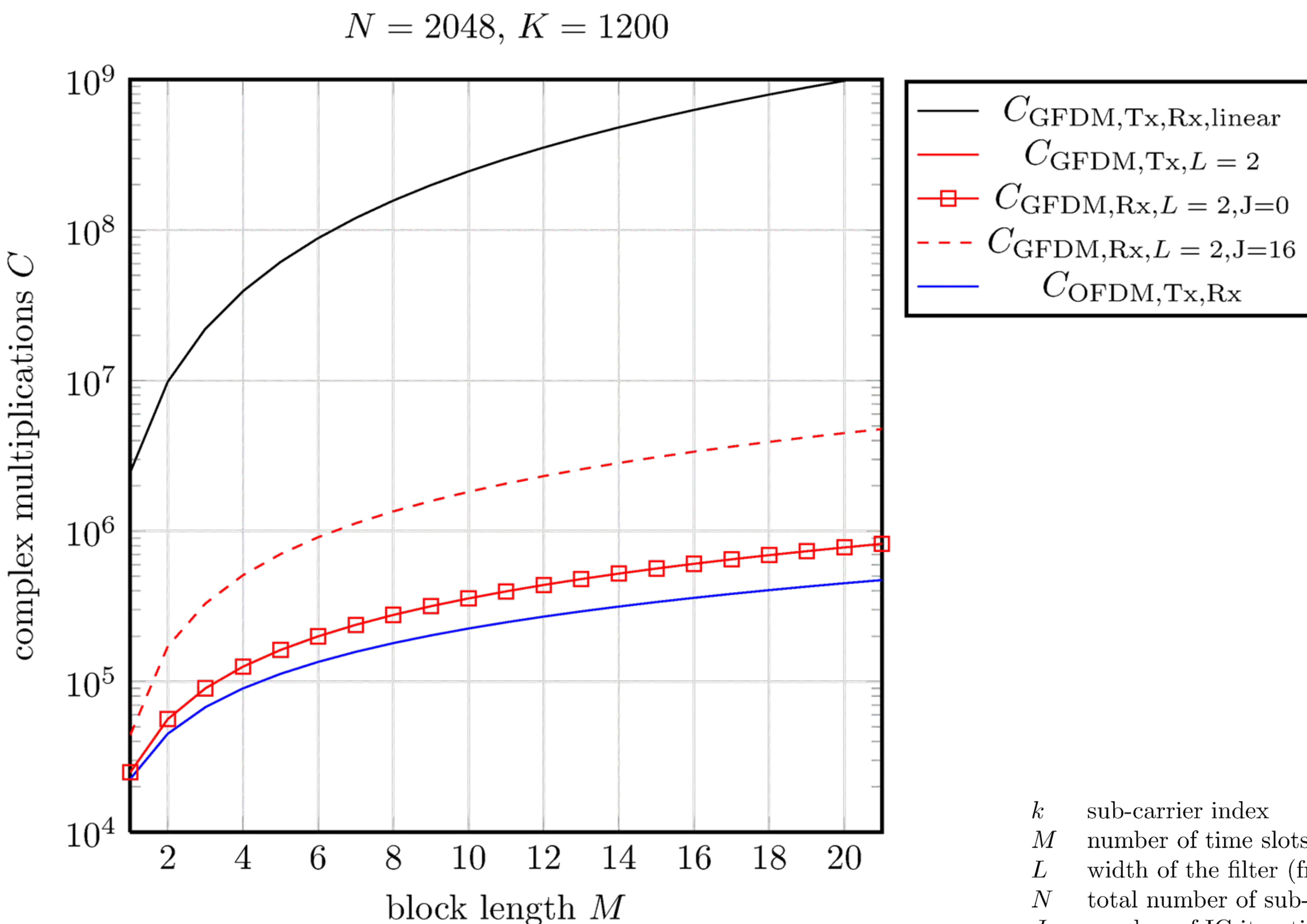
Per sub-carrier successive interference cancellation (IC) can be performed in frequency domain.

Receiver with IC





Complexity Analysis

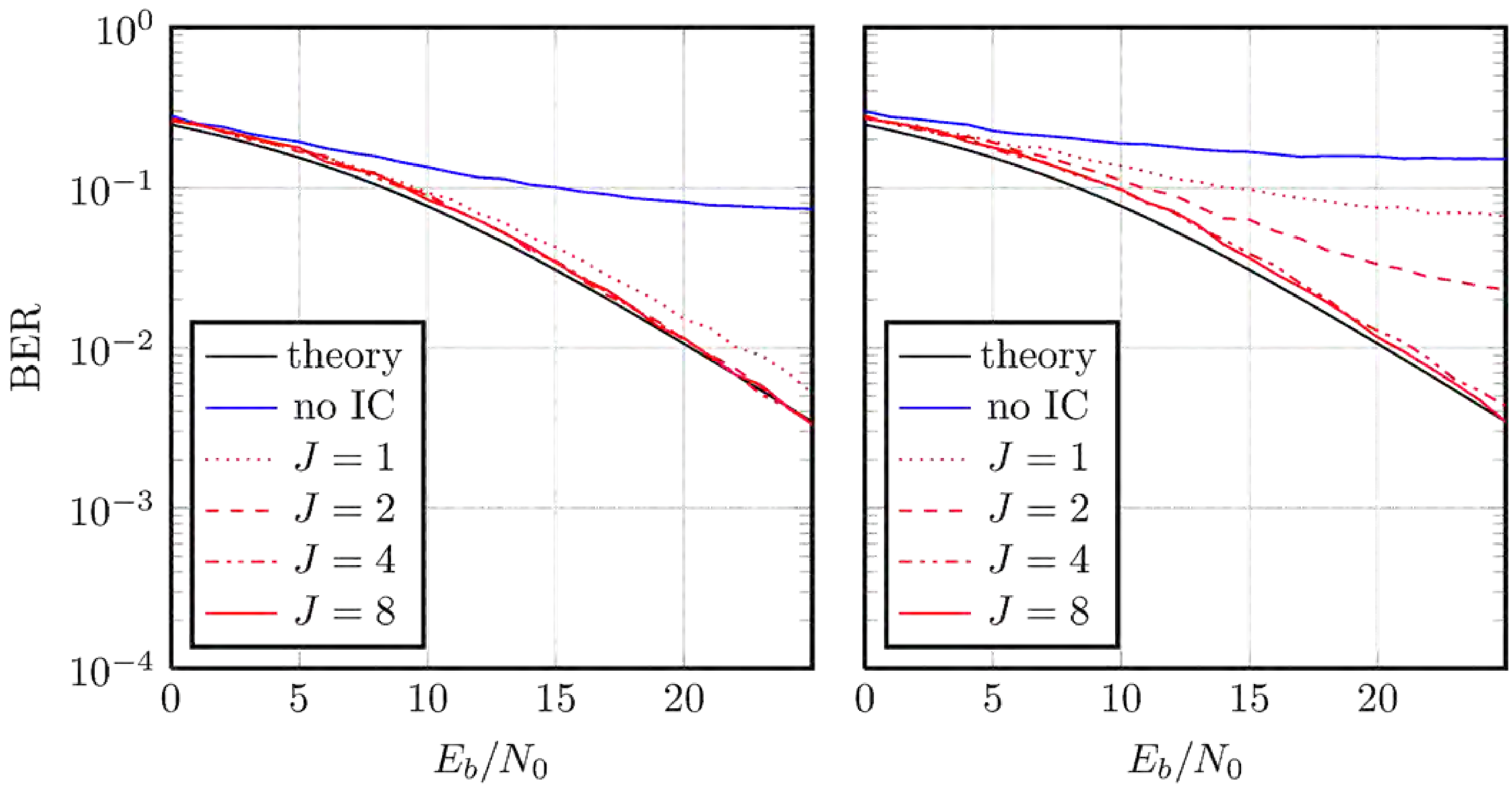


k	sub-carrier index
M	number of time slots per block
L	width of the filter (freq. domain)
N	total number of sub-carriers
J	number of IC iterations

ZF-FDE Bit Error Rate Performance

Rayleigh multipath

64QAM, RRC, a=0.2   64QAM, RRC, a=0.4   256QAM, RRC, a=0.4



CONCLUSIONS

The Tactile Internet Is Arriving With 5G

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Modulation	**OFDMA**	**GFDM**
Spectrum Shaping	spectrum mask, spectrum aggregation, and ACLR	Time-frequency spectrum engineering
Synchronous Operation	Requires frequency synchronous OFDMA and low phase noise	Robust against frequency offsets
Symbol Design	Physical limitations	FDE per subcarrier allows for flexibility

Selected Publications (GFDM System and Sensing)

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1. G. Fettweis, M. Krondorf, and S. Bittner, "**GFDM - Generalized Frequency Division Multiplexing**," in VTC Fall 2009, Barcelona, Spain.
2. I. Gaspar, N. Michailow, A. Navarro, E. Ohlmer, S. Krone, G. Fettweis,**"Low Complexity GFDM Receiver Based On Sparse Frequency Domain Processing,"** In Proc. of VTC Spring 2013, Dresden 2013.
3. R. Datta and G. Fettweis ''**Improved CR Spectrum Sensing Performance with Lower ACLR GFDM Signals**'' in Proceedings of IEICE'12, Fukuoka, Japan.
4. R. Datta, N. Michailow, M. Lentmaier, and G. Fettweis, "**GFDM Interference Cancellation for Flexible Cognitive Radio PHY Design**," in VTC Fall 2012, Quebec, Canada.
5. R. Datta, D. Panaitopol and G. Fettweis **''Analysis of Cyclostationary GFDM Signal Properties in Flexible Cognitive Radio**'' in Proceedings of the ISCIT'12, Gold Coast, Australia.
6. R. Datta, N. Michailow, S. Krone, M. Lentmaier and G. Fettweis ''**Generalized Frequency Division Multiplexing in Cognitive Radio''** in *Proceedings of EUSIPCO'12*, Bucharest, Romania.
7. R. Datta, K. Arshad and G. Fettweis ''**Analysis of Spectrum Sensing Characteristics for Cognitive Radio GFDM Signal''** in *Proceedings of IWCMC'12*, Limassol, Cyprus.
8. D. Panaitopol, R. Datta and G. Fettweis **''Cyclostationary Detection of Cognitive Radio Systems using GFDM Modulation**'' in Proceedings of WCNC'12, Paris, France.
9. N. Michailow, M. Lentmaier, P. Rost, and G. Fettweis, "**Integration of a GFDM Secondary System in an OFDM Primary System**," in *Future Network Summit, 2011*, Warshaw, Poland.
10. N. Michailow, I. Gaspar, S. Krone, M. Lentmaier and G. Fettweis ''**Generalized Frequency Division Multiplexing: An Alternative Multi-Carrier Technique for Next Generation Cellular Systems''** in *Proceedings of ISWCS'12*, Paris, France.

Selected Publications (GFDM System and Sensing)

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11. V. Berg, Z. Kollar, R. Datta, P. Horvath, D. Noguet and G. Fettweis, ‘‘**Low ACLR communication systems for TVWS operation‘‘** in *Proceedings of FuNeMs(FNMS'12)*, Berlin, Germany 2012.
12. R. Datta, G. Fettweis, Y. Futatsugi and M. Ariyoshi,‘‘**Comparative Analysis on Interference Suppressive Transmission Schemes for White Space Radio Access‘‘** in *Proceedings of the IEEE Vehicular Technology Conference (VTC Spring'12)*, Yokohama, Japan 2012.
13. R. Datta, G. Fettweis, Z. Kollar and P. Horvath ‘‘**FBMC and GFDM Interference Cancellation Schemes for Flexible Digital Radio PHY Design‘‘** in *Proceedings of the 14th EUROMICRO Conference*, Oulu, Finland, 2011.
14. R. Datta, G. Fettweis et.al,‘‘**Flexible Multicarrier PHY Design for Cognitive Radio in White Space‘‘** in *Proceedings of CrownCom'11*, Osaka, Japan, 2011.

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