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Mit Licht und Glas zu Petabit Kommunikationsnetzen

Peter J. Winzer
Nokia Bell Labs, Holmdel, NJ

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Immer mehr bandbreitenhungrige Internetanwendungen

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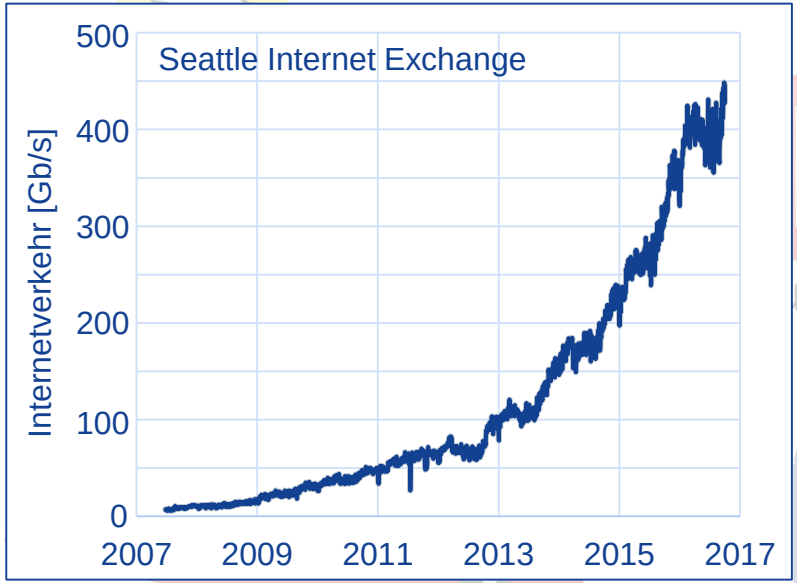
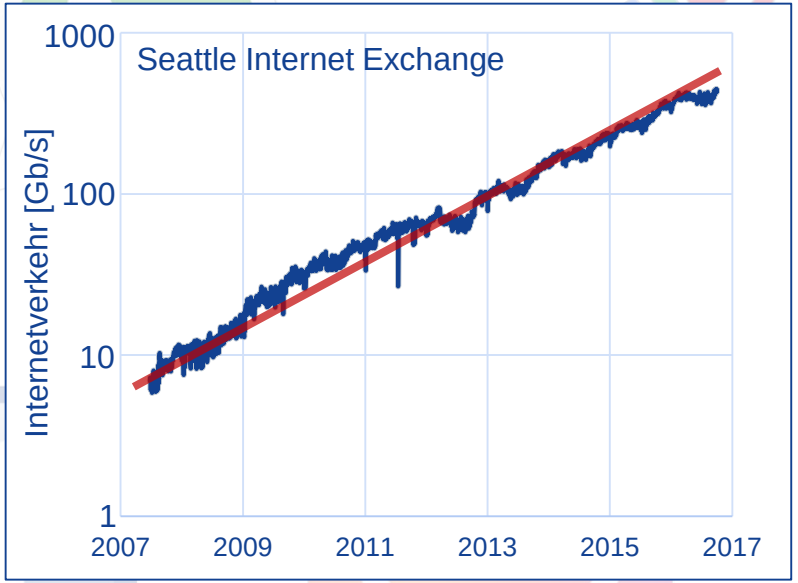
Exponentielles Verkehrswachstum





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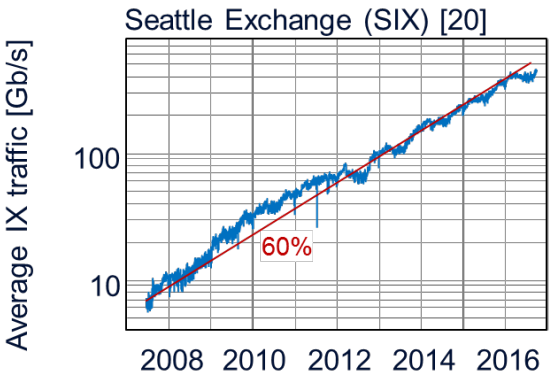
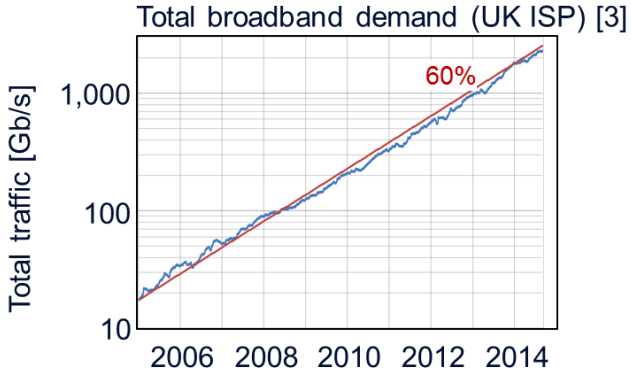
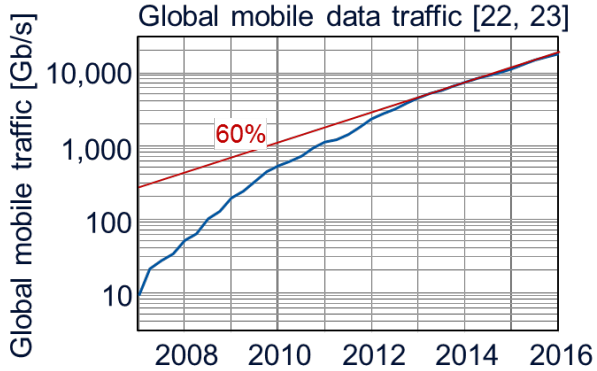
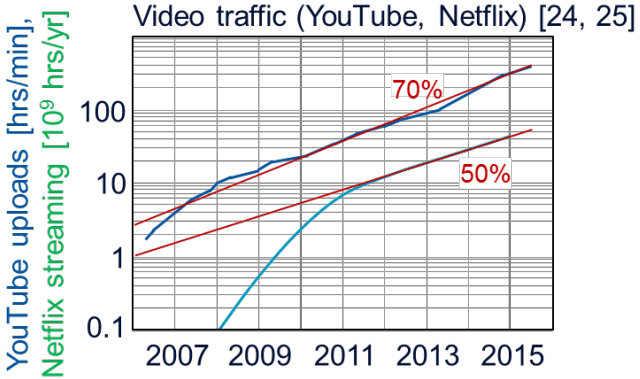
Exponentielles Verkehrswachstum durch immer neue Anwendungen









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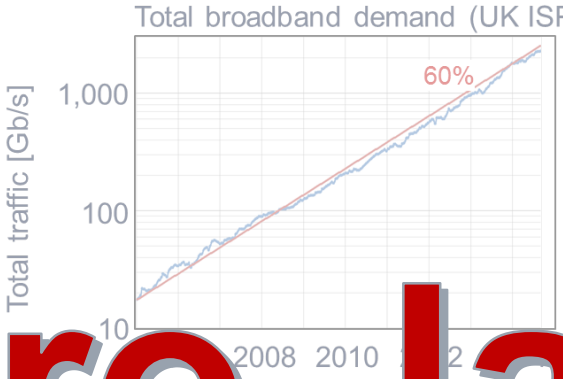

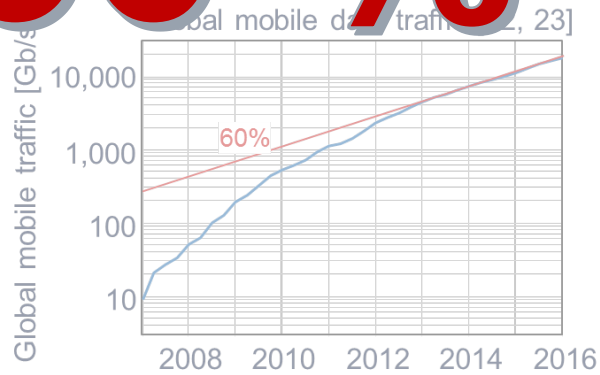

~60 % pro Jahr

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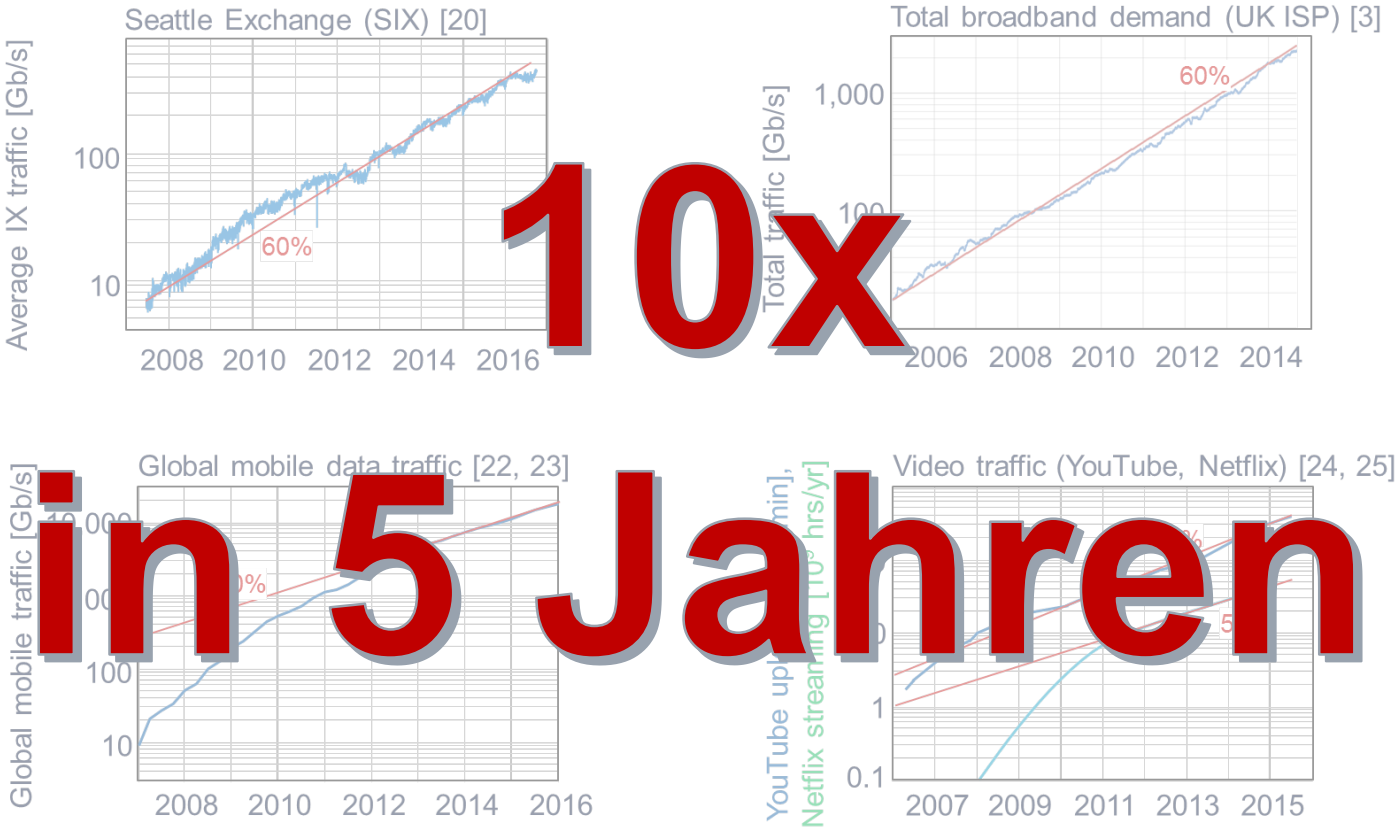
Exponentielles Verkehrswachstum durch immer neue Anwendungen



10x in 5 Jahren

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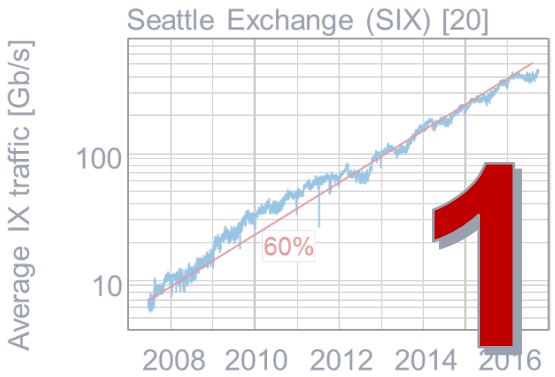
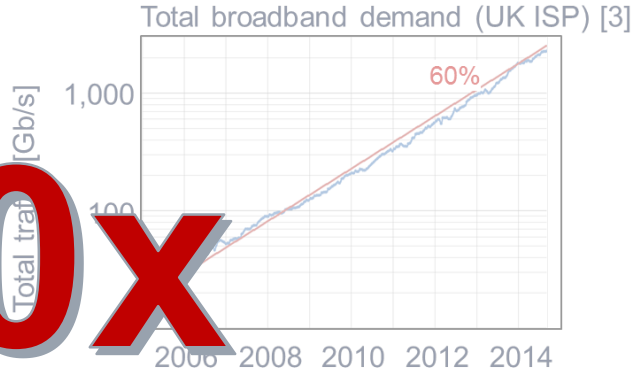
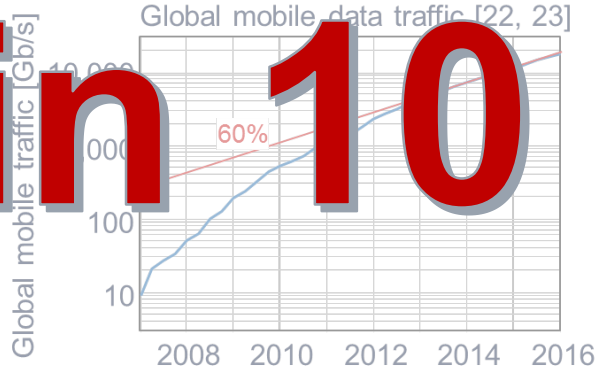
Exponentielles Verkehrswachstum durch immer neue Anwendungen





100x

in 10 Jahren



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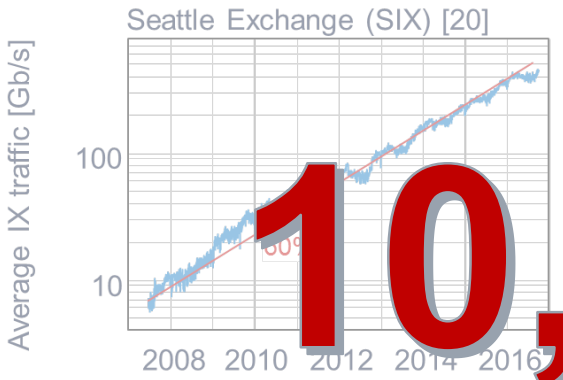
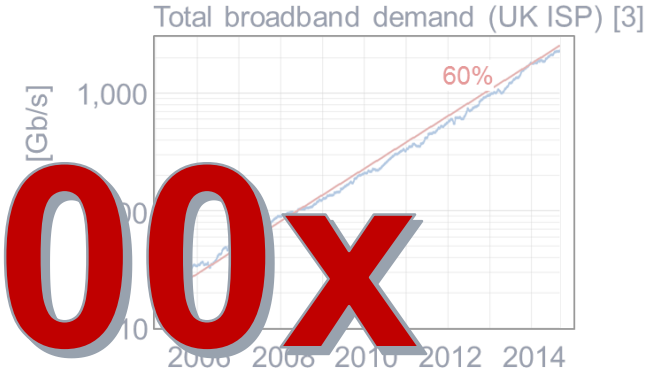
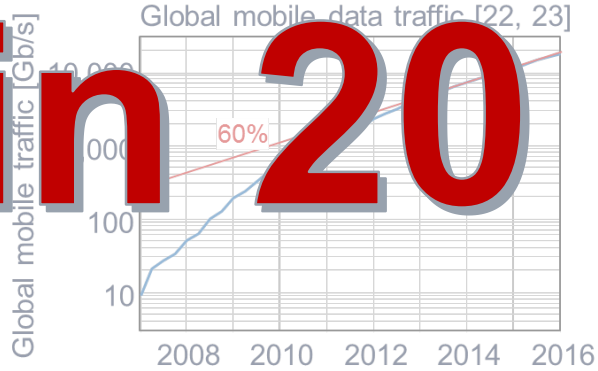
Exponentielles Verkehrswachstum durch immer neue Anwendungen







10,000x in 20 Jahren

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Wie lange kann so ein Wachstum noch bestehen ?

Woher soll all der Verkehr denn kommen ?

Ich weiss es nicht…

Niemand kann neue Anwendungen vorhersagen!

http://spacecollective.org/benrayfield/6799/Alternative-To-Brain-Implants

http://www.google.com/about/datacenters/
https://www.lsr.com/embedded-wireless-modules/tiwiconnect

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Wie lange kann so ein Wachstum noch bestehen ?

Woher soll all der Verkehr denn kommen ?

Ich weiss es nicht…

Niemand kann neue Anwendungen vorhersagen!

“There is no reason for any individual to have a computer in his home.”

Ken Olsen, Digital Equipment Corp., 1977

“… this quote is taken out of context and is not referring to personal computers …”

“… but to computers that control every aspect of home life: turning lights on and off, regulating temperature, choosing entertainments, monitoring food supplies, etc. The subject of this remark was not the personal-use computer, but the environment-regulating behemoth of science fiction.”

http://spacecollective.org/benrayfield/6799/Alternative-To-Brain-Implants

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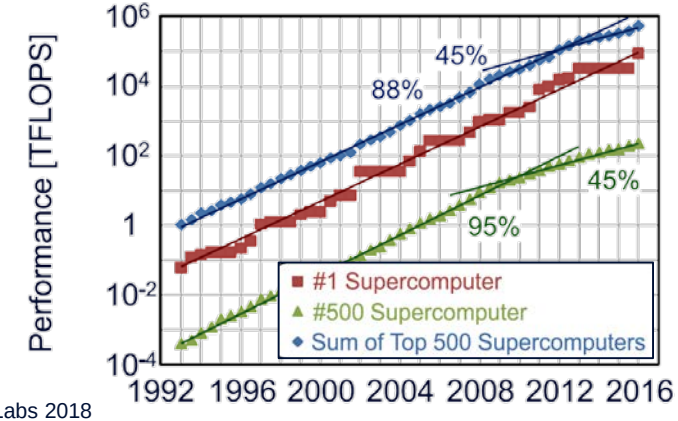
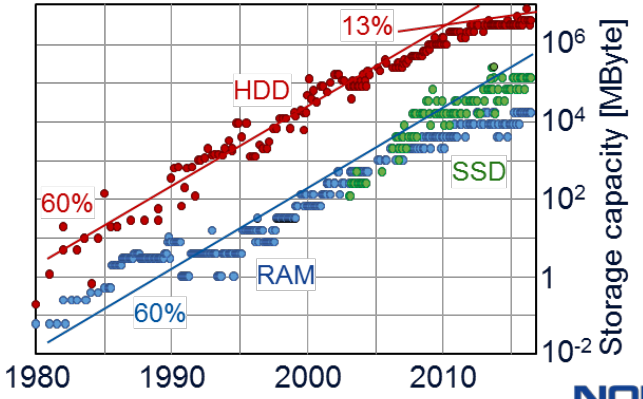
Technologische Treiber des Verkehrswachstums: Compute, Storage, Access

Erzeugung & Prozessierung von Information

Skalierung der Technologie	Exponentielle Trendperiode	Wachstumsrate
Supercomputer Rechenleistung	1995 – 2017	90%
Microprozessor Rechenleistung	1980 – 2017	40% - 70%
Speicherkapazität	1980 – 2017	60%
Core Router Kapazität	1985 – 2017	45%
Wireless Zugangskapazität	1995 – 2017	60%
Festnetz Zugangskapazität	1983 – 2017	40 - 55%

~60%





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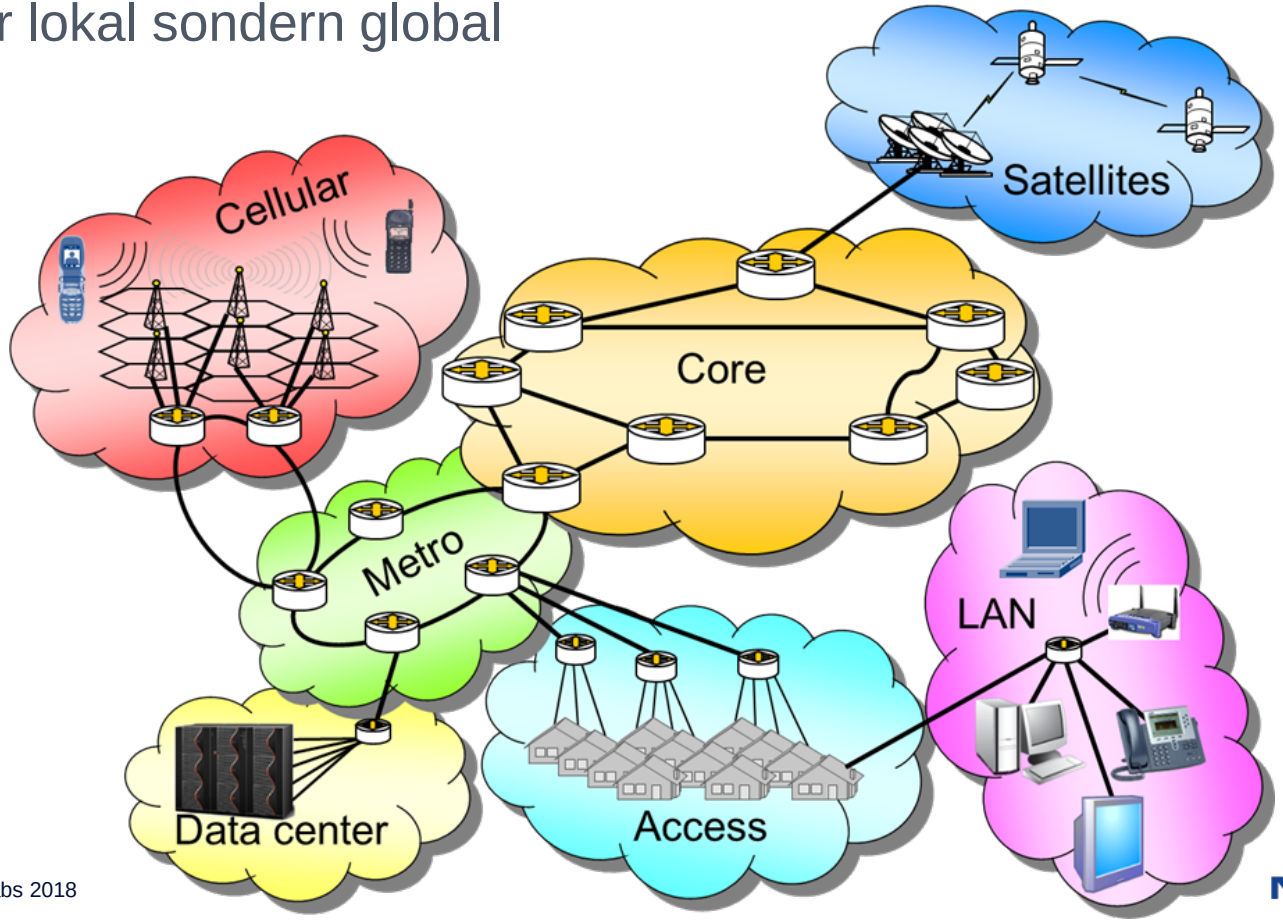
Der Sinn von Information ist sie zu kommunizieren …

… nicht nur lokal sondern global



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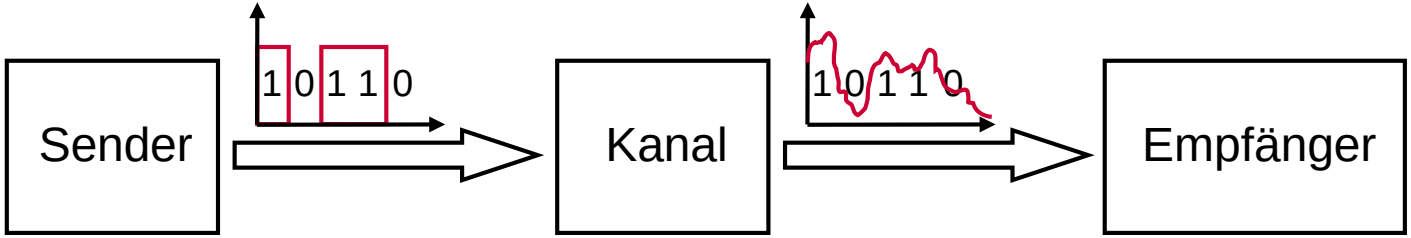
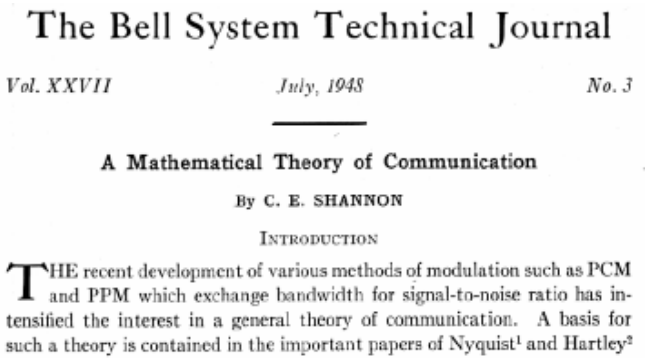
Wie wird Information am besten übertragen?
Digitale Kommunikation

- Digitale Information läßt sich *ohne Qualitätsverlust* transportieren und speichern (Claude Shannon, Bell Labs, 1948)





The Bell System Technical Journal

Vol. XXVII *July, 1948* *No. 3*

A Mathematical Theory of Communication

By C. E. SHANNON

INTRODUCTION

THE recent development of various methods of modulation such as PCM and PPM which exchange bandwidth for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist[1] and Hartley[2]

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Digitale Kommunikation

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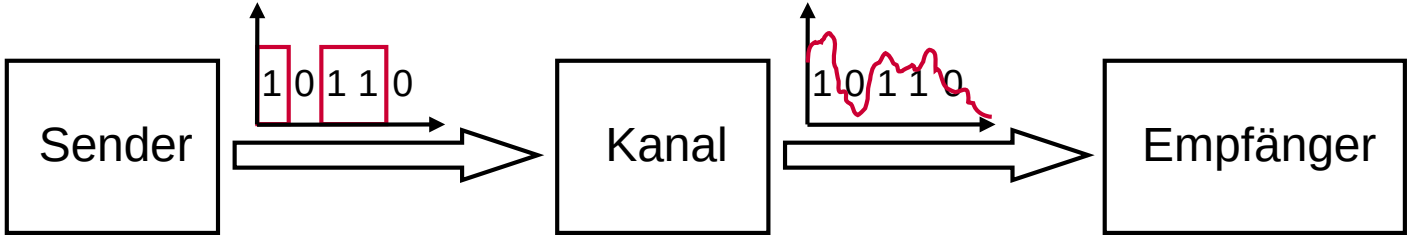
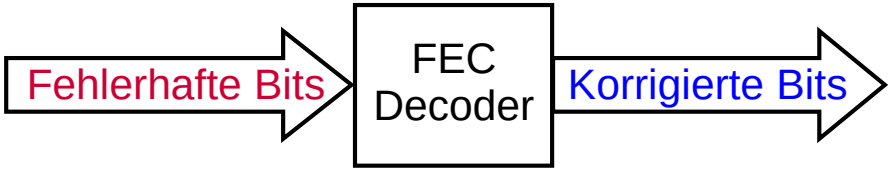


- Datenrate < Kanalkapazität (C)
- $C = B \log_2 (1 + SNR)$
- Einsatz fehlerkorrigierender Codes (FEC)



B: Bandbreite
SNR: Signal-zu-Rauschverhältnis

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Wie wird Information am besten übertragen?
Digitale Kommunikation

- Digitale Information läßt sich *ohne Qualitätsverlust* transportieren und speichern (Claude Shannon, Bell Labs, 1948)

- Digitale Komponenten sind universell einsetzbar
  → Massenmärkte
  → Universelle Systeme (selbe Technologie für Telefonie, Video, Internet, …)

- Digitale Komponenten müssen nicht gut sein
  → Kaum Linearitätsanforderungen
  → “Schlechte Schalter”
  → Miniaturisierung und Integration (~10 Milliarden Transistoren / Chip)
  → Kostenreduktion

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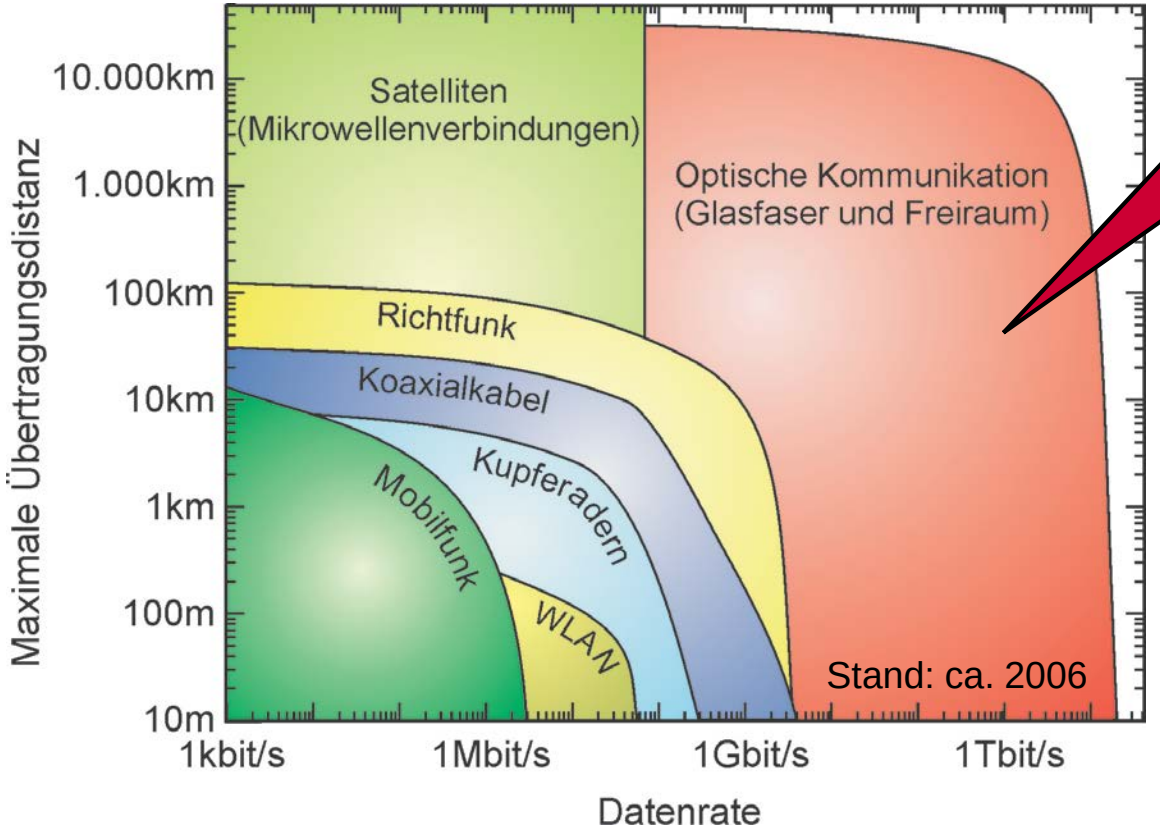
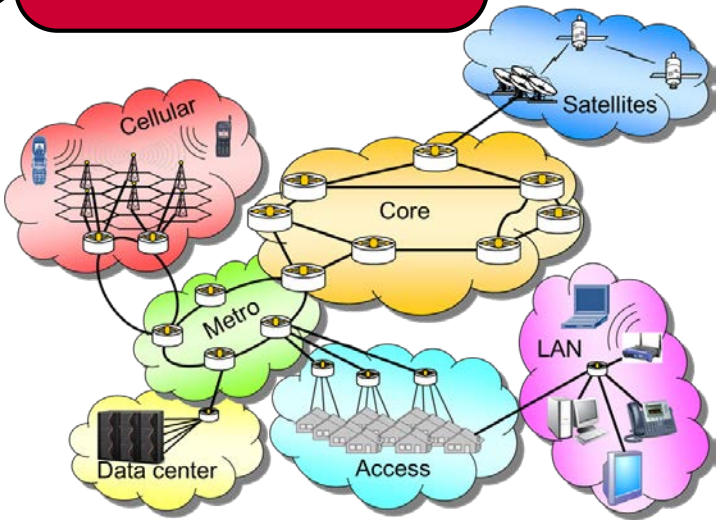
Welche Kommunikationstechnologie ist die richtige ?

Reichweite, Kapazität, Mobilität, Transmissionsmedium



Hohe Datenraten

Große Distanzen



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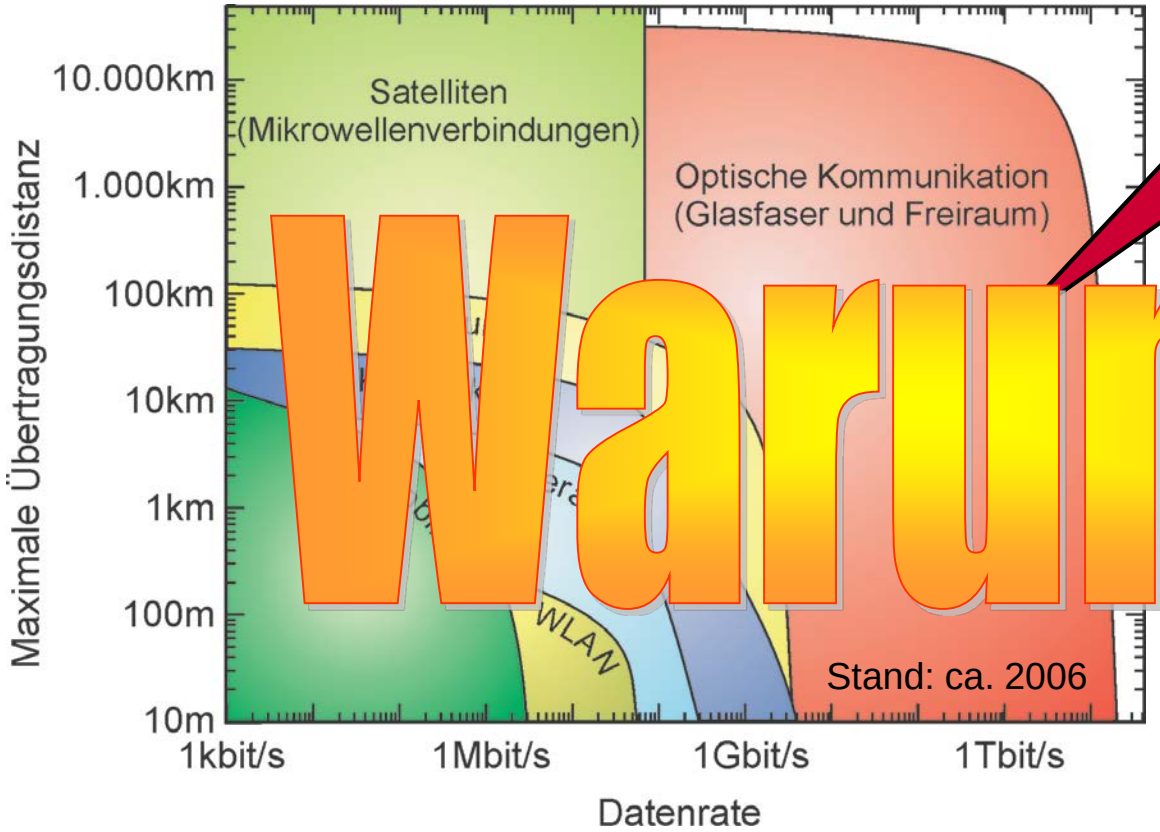
Welche Kommunikationstechnologie ist die richtige ?

Reichweite, Kapazität, Mobilität, Transmissionsmedium



Hohe Datenraten

Große Distanzen

Warum?

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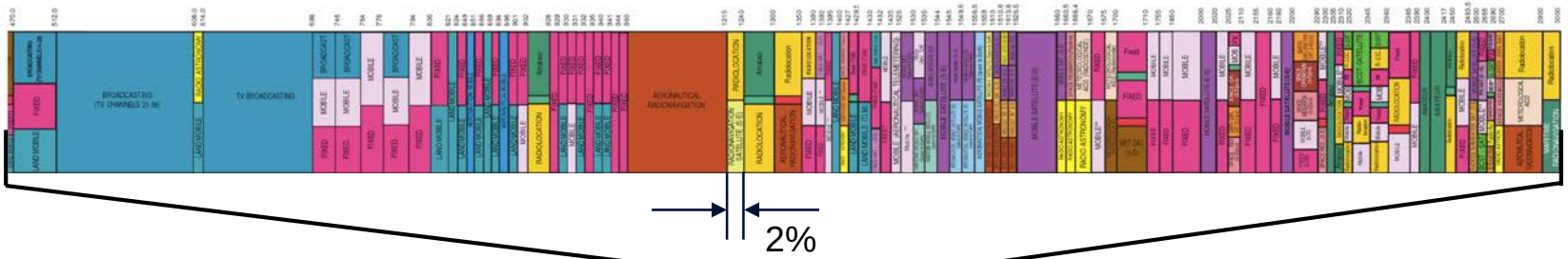
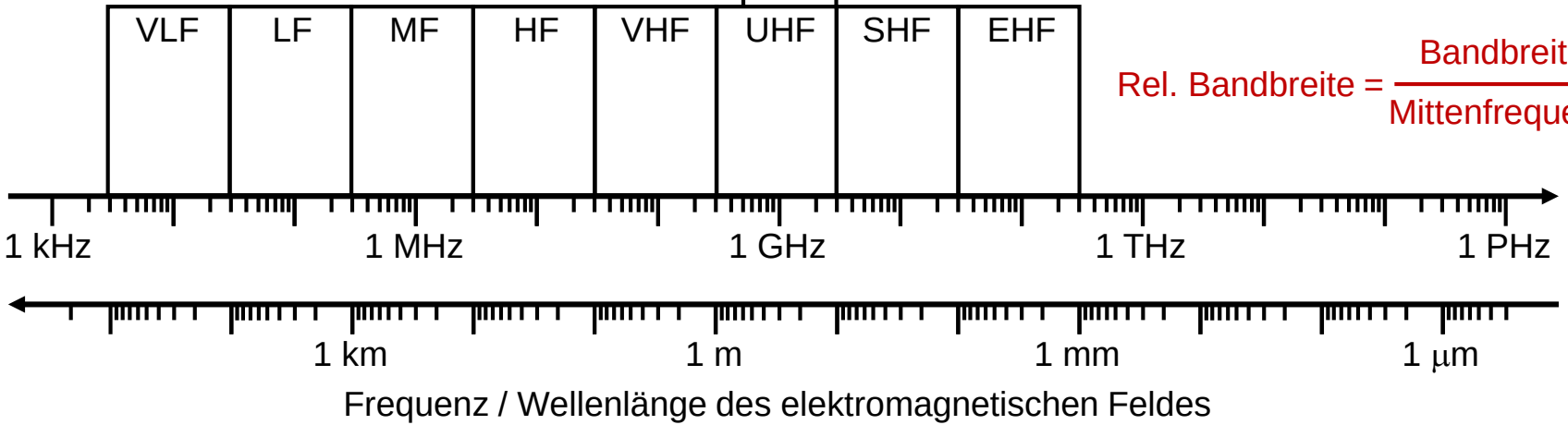
Elektromagnetische Kommunikationssysteme

Kleine *relative* Bandbreiten lassen sich einfacher realisieren als große





$$\text{Rel. Bandbreite} = \frac{\text{Bandbreite}}{\text{Mittenfrequenz}}$$

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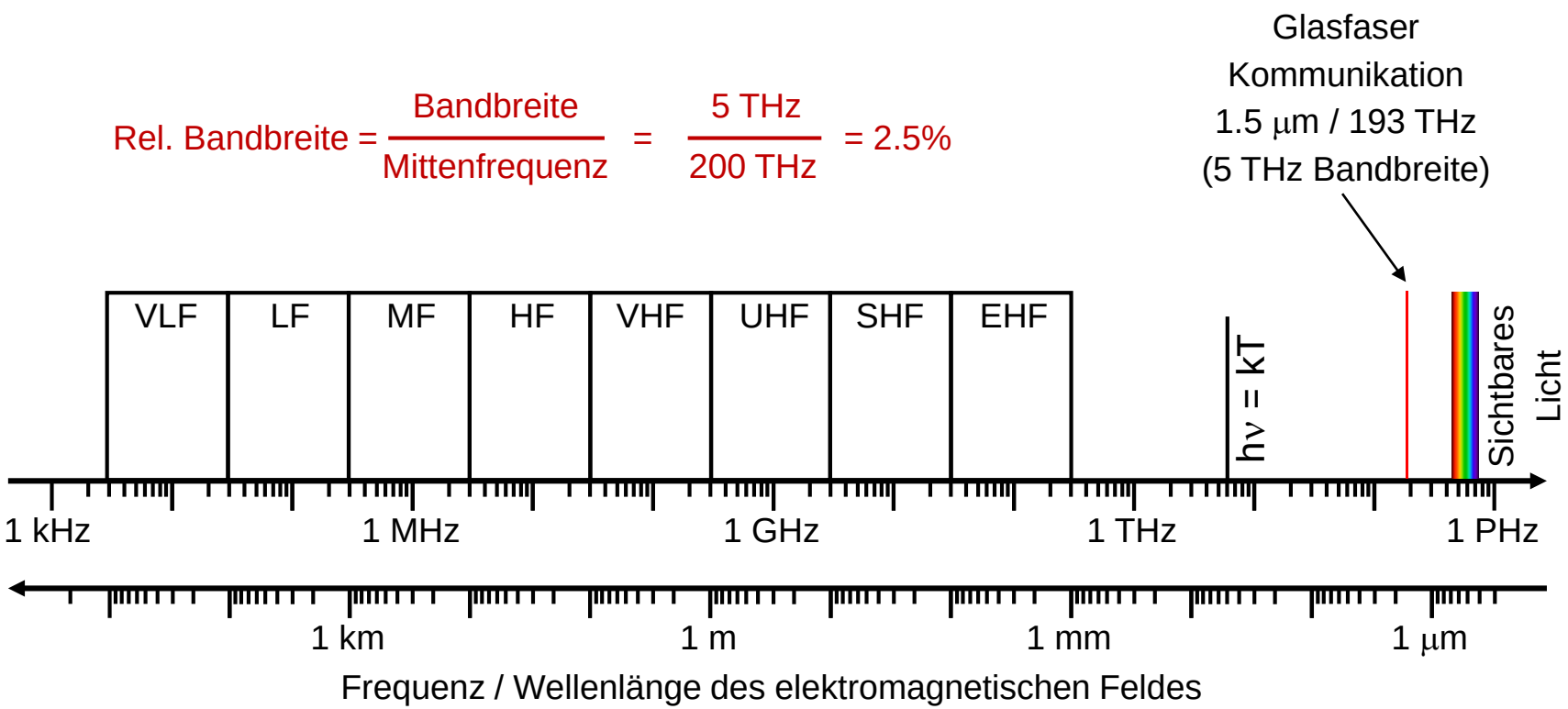
Optische Trägerfrequenzen

Grosse *absolute* Bandbreiten bei kleinen *relativen* Bandbreiten

$$\text{Rel. Bandbreite} = \frac{\text{Bandbreite}}{\text{Mittenfrequenz}} = \frac{5\ \text{THz}}{200\ \text{THz}} = 2.5\%$$



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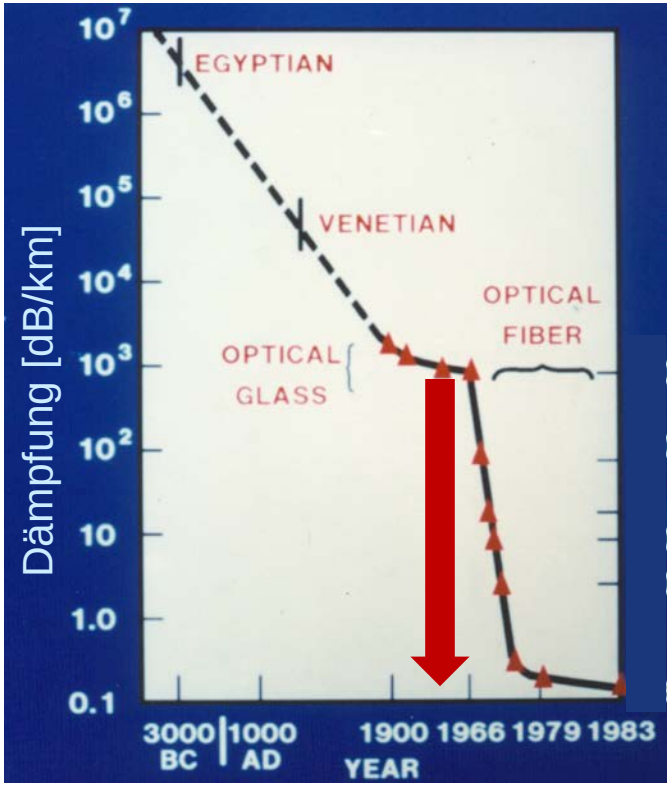
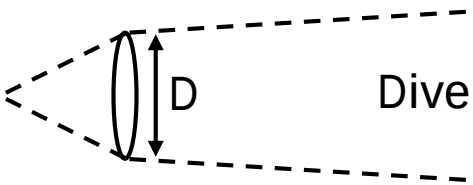
Geringe Dämpfungen

Auf Glasfasern und im freien Raum



Divergenz im freien Raum



Divergenzwinkel ~ λ / D

$$P_{RX} \sim P_{TX}\, D_{TX}^2 D_{RX}^2 / \lambda^2$$

z.B.: 200 THz statt 20 GHz

→ 10^8 x höherer Antennengewinn

(80 dB mehr Empfangsleistung)

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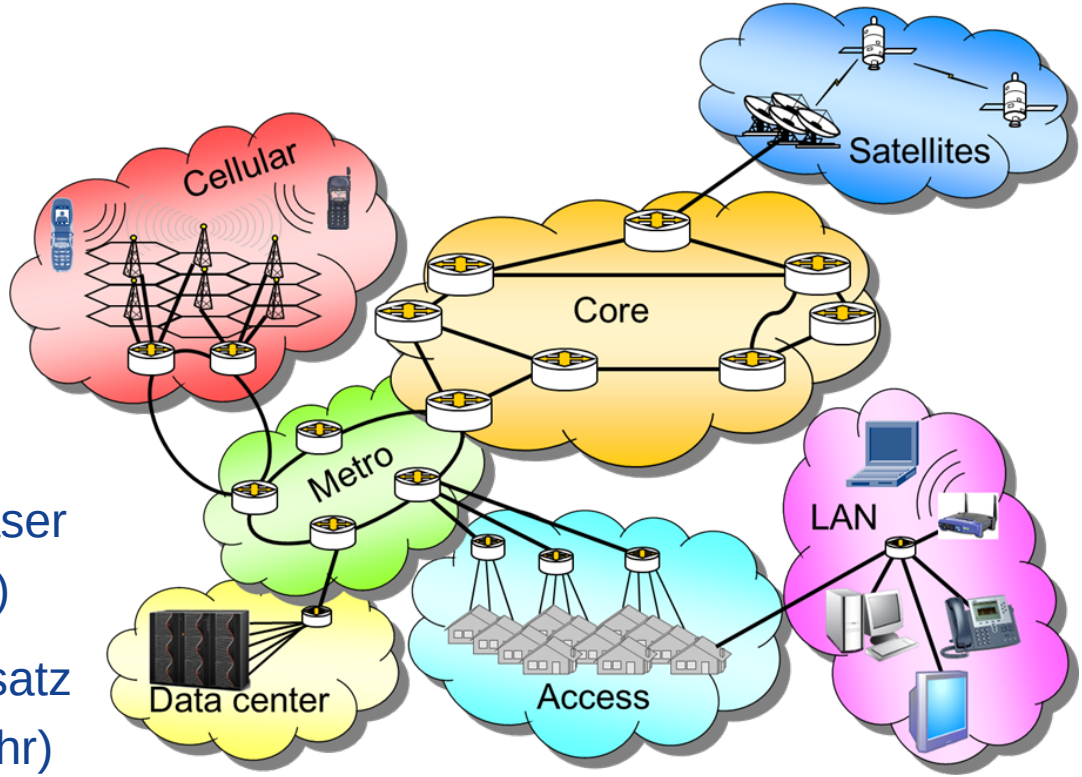
Grosse Bandbreite und geringe Dämpfung: Optische Glasfasernetze

Packesel des Internets: Fast jedes Informationsbit existiert als Photon

<u>Ein paar Zahlen:</u>

- 4 Milliarden km Faser installiert
  100,000x um die Erde
  13x zur Sonne und zurück
- 20 Terabit/s über 125 μm dicke Faser
  (5 Millionen 1080p Video Streams)
- 100 Petabit/s Transponder im Einsatz
  (1000x der weltweite Paketverkehr)



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Problem: Optische Informationskapazitäten wachsen nicht schnell genug

	Skalierung der Technologie	Exponentielle Trendperiode	Wachstumsrate
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	Festnetz Zugangskapazität	1983 – 2017	40 - 55%
Informations Transport	Paket Router Kapazität	1980 – 2005	70%
		2005 – 2017	**20%**
	Optische Transponderkapazität	**1985 – 2017**	**20%**
	Kapazität pro Faser	1995 – 2000	100%
		2000 – 2017	**20%**

~60%

!

~20%

In 5 Jahren: 4x Kluft

In 10 Jahren: 17x Kluft

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Optische Kommunikationsforschung = Den Packesel des Internets füttern

Andernfalls können Internetapplikationen nicht weiter wachsen!

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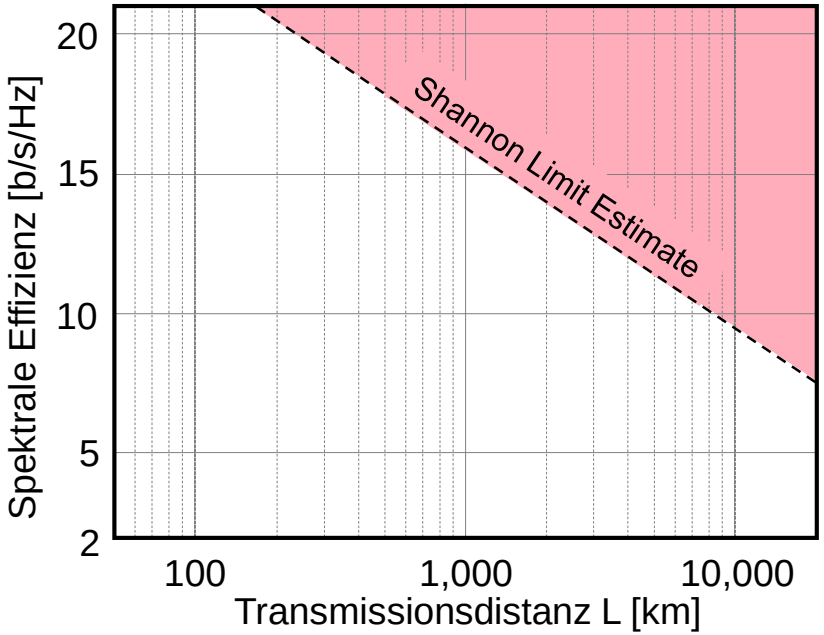
Der Grund ist fundamental: Shannon Limit der Faserkapazität



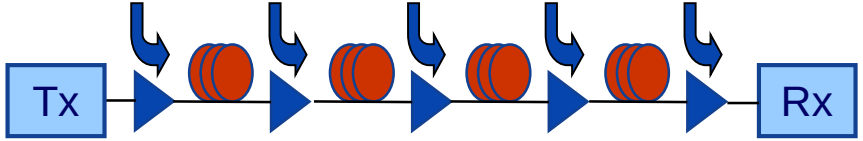
$C/B \sim 2 \log_2(1+SNR)$

$\sim L^{-1}$

Optisches Verstärkerrauschen

Nichtlineare Pulsverzerrungen

Verstärkerrauschen



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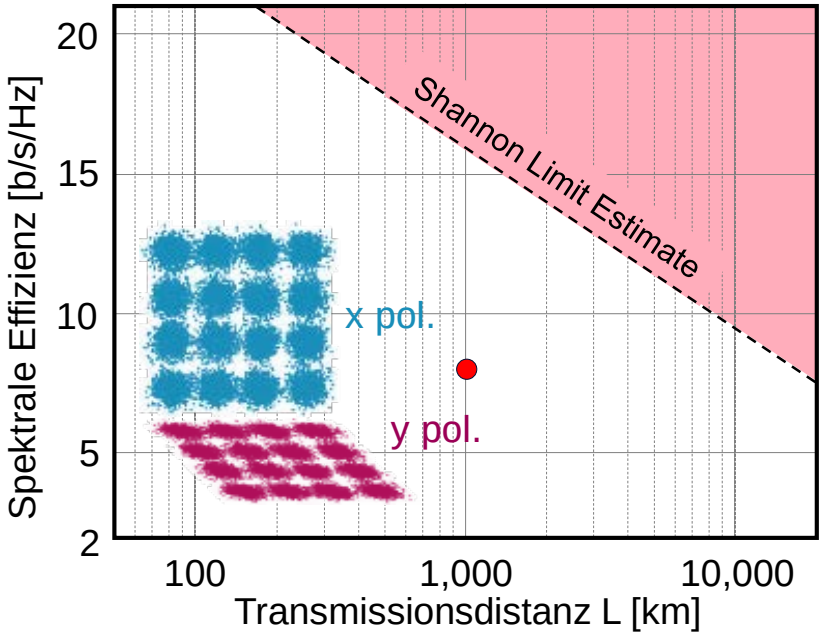
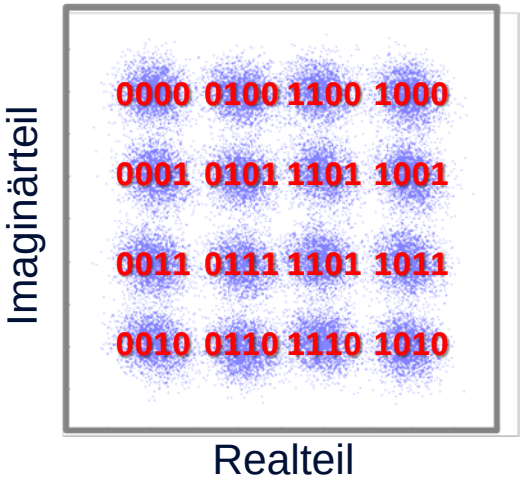
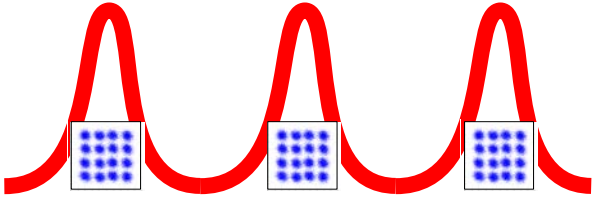
Modulation des komplexen optischen Feldes





$\log_2(M)$ Bits pro Puls



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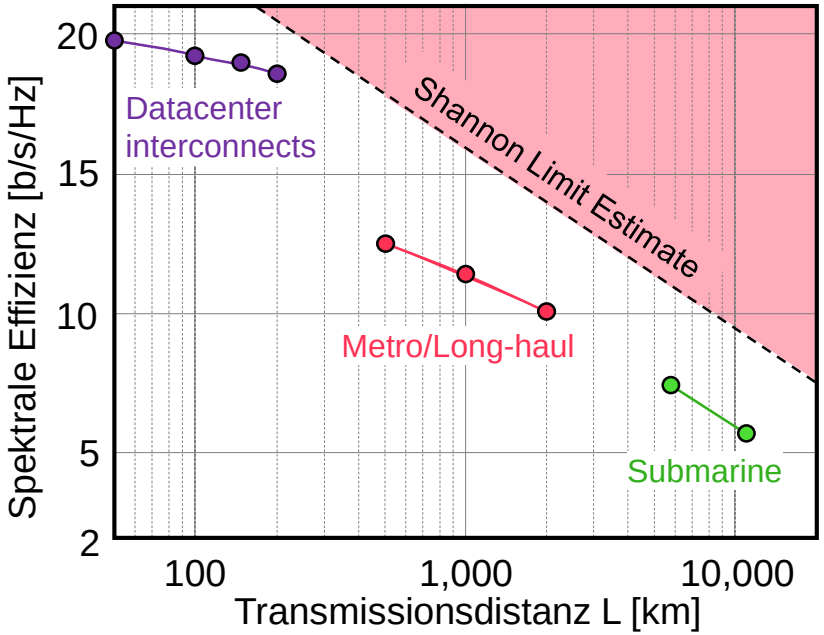
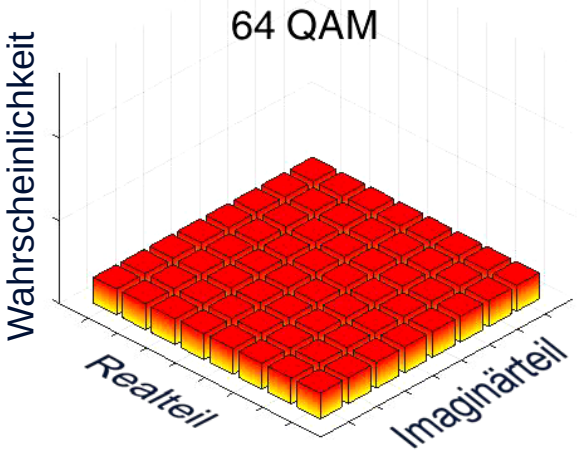
Rekordexperimente nähern sich rasch den fundamentalen Grenzen





Probabilistically Shaped

Quadrature Amplitude Modulation

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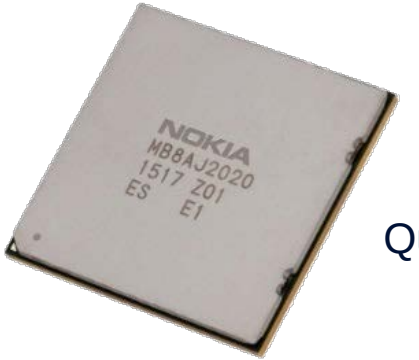
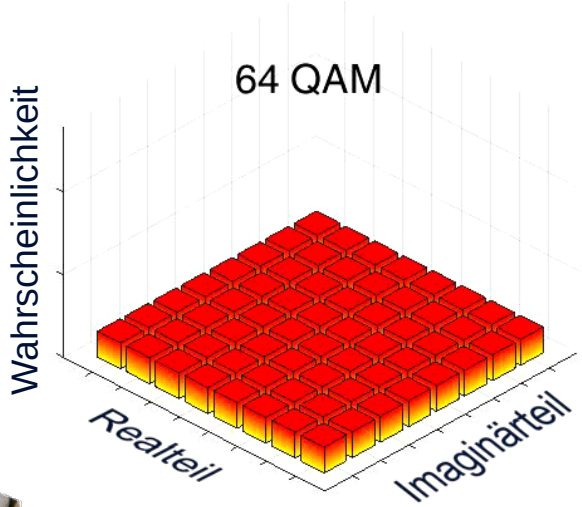
Gratulation der TU München https://www.bell-labs.com/prize/





Probabilistically Shaped

Quadrature Amplitude Modulation

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Transmissionsrekord auf Facebooks Fasern durch den Atlantik

Shirley,
NY, USA

5,523 km

11,046 km

Killala,
Ireland

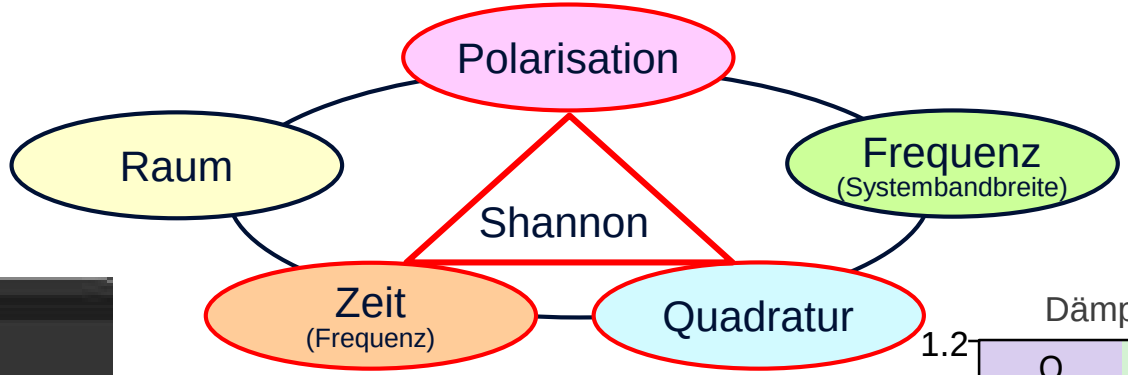
AEC-1 Unterseekabel

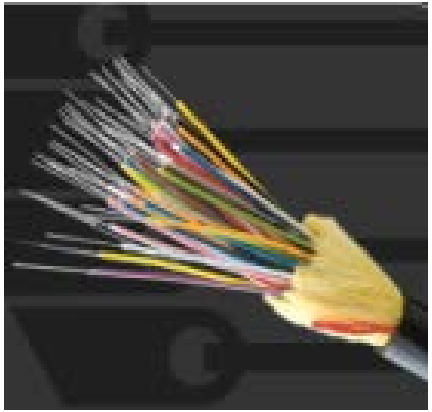
Rekordergebnisse:

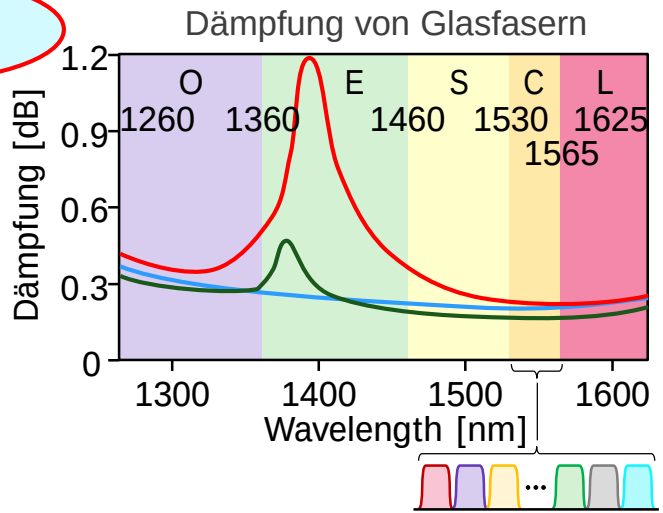
- 7.46 b/s/Hz (Trans-Atlantik)
- 5.68 b/s/Hz (Trans-Pazifik)

Wie geht's weiter? – Räumliche Parallelisierung

Fünf physikalische Dimensionen für Modulation und Multiplexing







Parallelisierung braucht Integration

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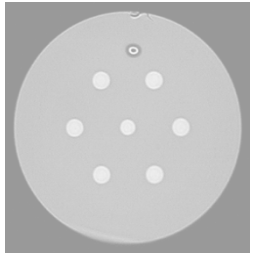
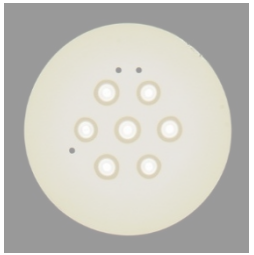
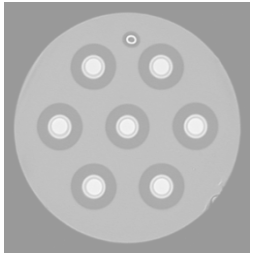
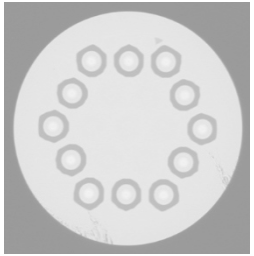
Integration paralleler Faserkanäle – Multi-core und Multi-mode Fasern

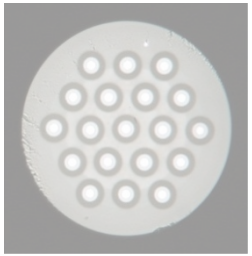
[Zhu, ECOC 2011]

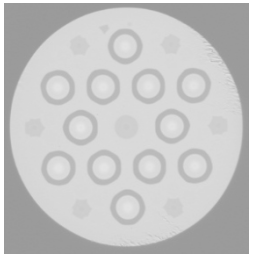

[Hayashi, ECOC 2011]


[Imamura, ECOC 2011]


[Hayashi, OFC 2011]


[Takara, ECOC 2012]

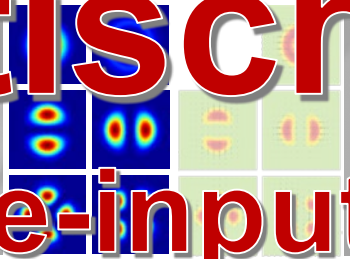

[Sakaguchi, OFC 2012]


[Kobayashi, ECOC 2013]

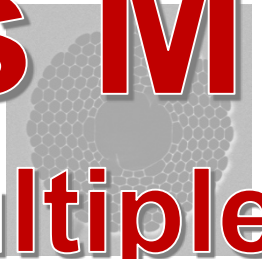
Optisches MIMO
(Multiple-input/multiple-output)

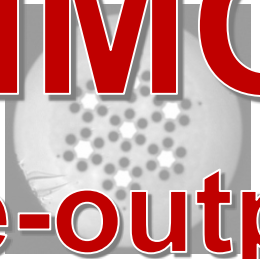
[Ryf, ECOC 2011]

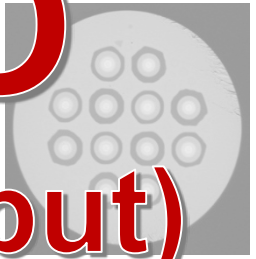
[Ryf, FiO 2012]

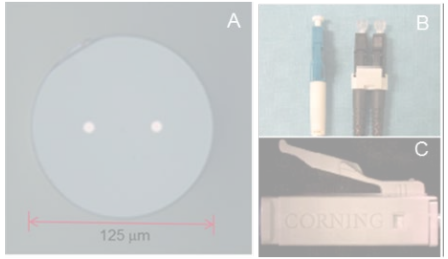


[Doerr, ECOC 2011]

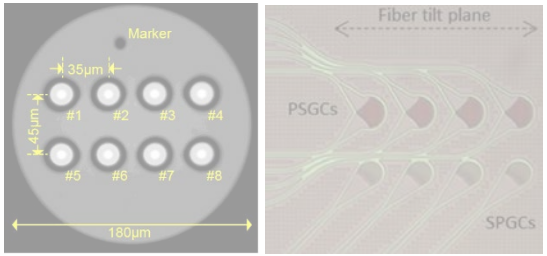

[Petrovich, ECOC 2012]


[Cia, IPS SumTop 2014]


[Mizuno, OFC 2014]



[Y. Geng et al., SPIE 2015]



[T. Hayashi et al., ECOC 2017]

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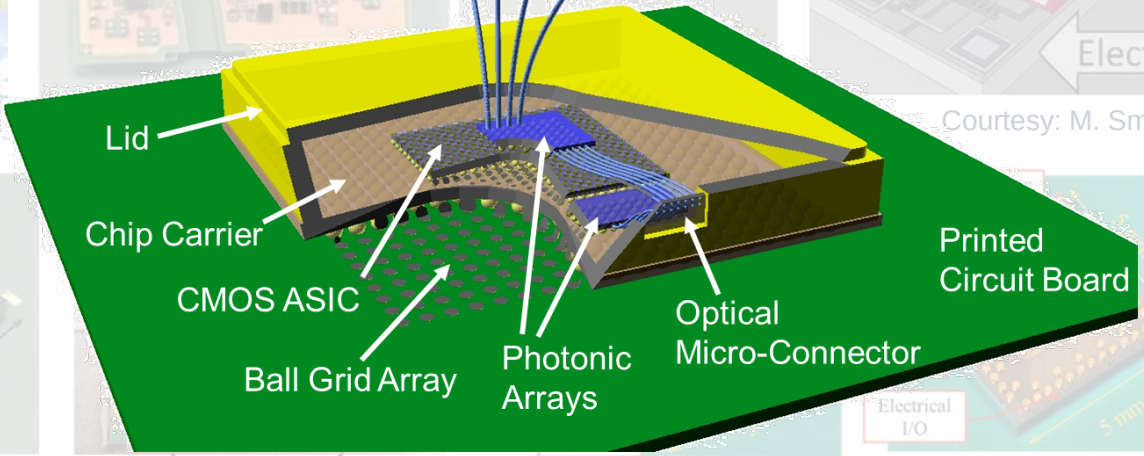
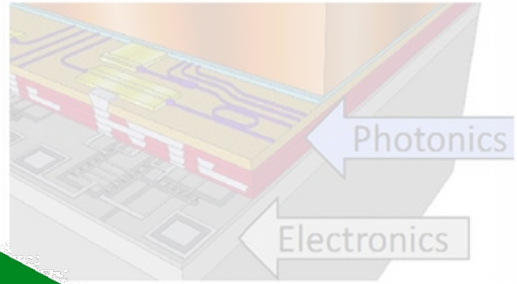
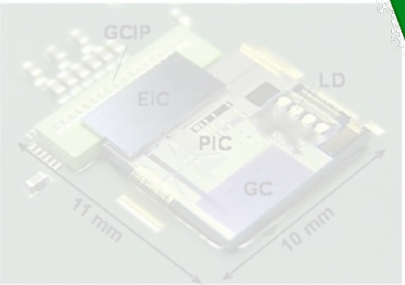
Opto-elektronische Transponderintegration – Faser in / Faser out (FIFO)

[Y. De Koninck, ECOC 2017]



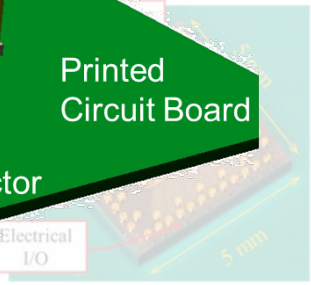


Courtesy: M. Smit, K. Williams



[T. Aoki, ECOC 2017]

[M. Rakowski et al., OFC 2013]



[K. Yashiki et al., OFC 2015]

FIFO Prozessoren

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