Abstract: Over the last couple of years in particular, THz communications, i.e. the frequency range beyond 275 GHz, has become an attractive new research area for commercial development. It has reached a level of maturity that a couple of projects are now underway to develop technological solutions enabling the set-up of hardware demonstrators. This tutorial will provide a brief overview on the current status of THz Communication systems focusing on ongoing research activities such as the European Horizon 2020 framework, and provide an overview of the ongoing WRC 2019 preparations, as well as discussing the potential for IEEE 802 to play a major role in this interesting frequency range.

Purpose: Tutorial on the activities and the status of the IEEE 802.15 TAG THz presented to the IEEE 802 Plenary

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THz Communications – An Overview and Options for IEEE 802 Standardization

Tutorial at IEEE 802 Plenary, November 2018
by IEEE 802.15 TAG THz

Presenters:
Thomas Kürner, TU Braunschweig, Germany
Akifumi Kasamatsu, NICT, Japan
Onur Sahin, InterDigital, UK
Carlos Castro, Fraunhofer Heinrich Hertz Institute, Germany
Outline

• Status on THz Communication in Standardisation, Regulation and Research (Thomas Kürner)
• Silicon CMOS Transceiver for Terahertz Wireless Communication (Akifumi Kasamatsu)
• Towards Ultra-High Throughput FEC Design: EPIC Project (Onur Sahin)
• Integration of fiber-optics/THz Technologies (Carlos Castro)
• Conclusion and Outlook (Thomas Kürner)
Status on THz Communication in Standardisation, Regulation and Research

Thomas Kürner, Sebastian Rey, Johannes Eckhardt

Technische Universität Braunschweig, Germany
Motivation for THz Communications

Temporal Evolution of Data Rates in Transmission Schemes

- Backhaul/Fronthaul links
  - 10..100 Gbit/s
  - Applications (as in IEEE Std. 802.15.3d-2017)

- Wireless Links in Data Centers
  - 10...100 Gbit/s

- Intra-Device Communication
  - 10...100 Gbit/s

> 20 GHz Bandwidth @ 300 GHz +
STATUS IN
STANDARDISATION
IEEE Std. 802.15.3d-2017

Key Facts

– New PHY for Std. IEEE 802.15.3-2016
– MAC is mainly based on IEEE 802.15.3e-2017, which introduced the concept of “Pairnet”
  • Point-to-point nature with highly-directive antennas reduces the problem of interference and “fighting for access”
  • Positions of Tx and Rx antennas are known
– 8 different channel bandwidths (as multiples of 2.16 GHz)
– 2 PHY-modes (THz-SC PHY, THz-OOK-PHY) with 7 modulation schemes:
  • BPSK, QPSK, 8-PSK, 8-APSK, 16-QAM, 64 QAM, OOK
– 3 channel coding schemes:
Channel plan
Exemplary Simulation Results for Backhaul/Fronthaul Applications

- Assumption of a margin of 20 dB for atmospheric attenuation

<table>
<thead>
<tr>
<th>MCS Identifier</th>
<th>Modulation</th>
<th>FEC Rate</th>
<th>Maximum Link Distance in m (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>BPSK</td>
<td>11/15</td>
<td>5343 3778 2671 2181 1889 1542 1091 944</td>
</tr>
<tr>
<td>1</td>
<td>BPSK</td>
<td>14/15</td>
<td>3646 2578 1823 1488 1289 1052 744 644</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>11/15</td>
<td>3796 2684 1898 1550 1342 1096 775 671</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>14/15</td>
<td>2563 1812 1282 1046 906 740 523 453</td>
</tr>
<tr>
<td>4</td>
<td>8-PSK</td>
<td>11/15</td>
<td>2157 1525 1078 880 762 623 440 381</td>
</tr>
<tr>
<td>5</td>
<td>8-PSK</td>
<td>14/15</td>
<td>1725 1220 862 704 610 498 352 305</td>
</tr>
<tr>
<td>6</td>
<td>8-APSK</td>
<td>11/15</td>
<td>2157 1525 1078 880 762 623 440 381</td>
</tr>
<tr>
<td>7</td>
<td>8-APSK</td>
<td>14/15</td>
<td>1729 1223 864 706 611 499 353 306</td>
</tr>
<tr>
<td>8</td>
<td>16-QAM</td>
<td>11/15</td>
<td>1709 1209 855 698 604 493 349 302</td>
</tr>
<tr>
<td>9</td>
<td>16-QAM</td>
<td>14/15</td>
<td>1152 814 576 470 407 332 235 204</td>
</tr>
<tr>
<td>10</td>
<td>64-QAM</td>
<td>11/15</td>
<td>949 671 475 387 336 274 194 168</td>
</tr>
<tr>
<td>11</td>
<td>64-QAM</td>
<td>14/15</td>
<td>581 411 291 237 205 168 119 103</td>
</tr>
</tbody>
</table>

Source: doc. IEEE 802.15-17-0039-04-003d
STATUS IN REGULATION
Starting point for Radio Regulations: Outcome of WRC 2012

- 5.565 A number of bands in the frequency range 275-1 000 GHz are identified for use by administrations for passive service applications. The following specific frequency bands are identified for measurements by passive services:
  - radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453-510 GHz, 623-711 GHz, 795-909 GHz and 926-945 GHz;

- The use of the range 275-1 000 GHz by the passive services does not preclude use of this range by active services.

- Administrations wishing to make frequencies in the 275-1 000 GHz range available for active service applications are urged to take all practicable steps to protect these passive services from harmful interference until the date when the Table of Frequency Allocations is established in the above-mentioned 275-1 000 GHz frequency range.

- All frequencies in the range 1 000-3 000 GHz may be used by both active and passive services. (WRC-12)
Possible Interference Scenarios to be studied

Nomadic Links

Multiple Interferers

Fixed Links

Current status of the preparatory work of AI 1.15 @ WRC 2019

• WRC 2015 agreed in resolution 767:
  – to have an agenda item for WRC 2019 to consider identification of spectrum for land-mobile and fixed active services in the range of 275 GHz to 450 GHz while maintaining protection of the passive services identified in the existing footnote 5.565.

Current Status
– Regarding the new active services the reports ITU-R F.2416 and ITU-R M.2417 have been published.
– The frequency bands of interest are
  • between 275 to 450 GHz for land mobile applications.
  • especially, 275-325 GHz and 380-445 GHz for fixed service applications
– ITU-R WP 1A is conducting sharing studies and preliminary results are available.
  • For instances in the band 275 to 296 GHz coexistence with the passive services seems to be possible. This provides a continues bandwidth of 44 GHz with the existing band from 252-275 GHz.
  • Other bands are under consideration.
RECENT ACTIVITIES IN THE EU-RESEARCH PROGRAM HORIZON 2020
H2020-ICT-09-2017-Cluster on Networks Beyond 5G

- Seven funded projects from the H2020 calls ICT-09-2017 and EUJ-02-2018 form an informal cluster
  
  [Visit this website](https://thorproject.eu/links/ict-09-2017-cluster)

  - DREAM: D-band Radio solution Enabling up to 100 Gb/s reconfigurable Approach for Meshed beyond 5G network
  - EPIC: Enabling Practical Wireless Tb/s Communications with Next Generation Channel Coding
  - TERAPOD: Terahertz based Ultra High Bandwidth Wireless Access Networks
  - TERRANOVA: Terabit/s Wireless Connectivity by Terahertz Innovative Technologies to deliver Optical Network Quality of Experience in Systems Beyond 5G
  - ULTRAWAVE: Ultra capacity wireless layer beyond 100 GHz based on millimeter wave Traveling Wave Tubes
  - WORTECS: Wireless Optical/Radio Terabit Communications
  - ThoR: TeraHertz end-to-end wireless systems supporting ultra high data Rate applications
Horizon 2020 Project TERAPOD

• Project Duration: September 2017 – August 2020

• Project Goals:
  – to investigate and demonstrate the feasibility of ultra high bandwidth wireless access networks operating in the Terahertz band.
  – The project will focus on end to end *demonstration of the THz wireless link within a Data Centre Proof of Concept deployment*, while also investigating other use cases applicable to beyond 5G
  – The project seeks to bring THz communication a leap closer to industry uptake through leveraging recent advances in THz components, a thorough measurement and characterization study of components and devices, coupled with specification and validation of higher layer communication protocol specification.

• The TERAPOD project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 761579

• Web Page: www.terapod-project.eu
Some first Results from TERAPOD

- 300 GHz channel measurements in the Research Data Center of Dell/EMC using the time-domain channel sounder (approx. 8 GHz of bandwidth) available at TU Braunschweig

For more information see doc. IEEE 802.15-18-0519-00-0thz
Horizon 2020 EU-Japan Project ThoR on THz Backhaul/Fronthaul Links

- Project duration 1.7.2018-30.6.2020
- ThoR is equally funded from
  - Horizon 2020, the European Union’s Framework Programme for Research and Innovation, under grant agreement No. 814523 and
  - the National Institute of Information and Communications Technology in Japan (NICT)

Web page: www.thorproject.eu

<table>
<thead>
<tr>
<th>Participants</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Companies</strong></td>
<td></td>
</tr>
<tr>
<td>Deutsche Telekom AG</td>
<td>Germany</td>
</tr>
<tr>
<td>NEC Corporation</td>
<td>Japan</td>
</tr>
<tr>
<td>Siklu Communication Ltd.</td>
<td>Israel</td>
</tr>
<tr>
<td>Vivid Components Ltd.</td>
<td>UK</td>
</tr>
<tr>
<td>HRCP</td>
<td>Japan</td>
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<tr>
<td><strong>R&amp;D</strong></td>
<td></td>
</tr>
<tr>
<td>Fraunhofer IAF</td>
<td>Germany</td>
</tr>
<tr>
<td>University of Lille / IEMN Laboratory</td>
<td>France</td>
</tr>
<tr>
<td><strong>Universities</strong></td>
<td></td>
</tr>
<tr>
<td>TU Braunschweig (Coordinator, EU)</td>
<td>Germany</td>
</tr>
<tr>
<td>Chiba Institute of Technology</td>
<td>Japan</td>
</tr>
<tr>
<td>Gifu University</td>
<td>Japan</td>
</tr>
<tr>
<td>University of Stuttgart</td>
<td>Germany</td>
</tr>
<tr>
<td>Waseda University (Coord., Japan)</td>
<td>Japan</td>
</tr>
</tbody>
</table>
ThoR Concept towards the Demonstration of a 300 GHz Link for Backhaul/Fronthaul

Key Enabling Technologies (KETs)
1. Photonics-based LO
2. Electronic THz amplifier and up-converter
3. High Power THz traveling-wave tube amplifier
4. Electronic THz receiver
5. Digital baseband and networking interface
6. Contributions to spectrum regulation and interference mitigation

Key Performance Indicators (KPIs)
1. Transmitter linearity, bandwidth & output power
2. Spectral purity of photonic THz LO
3. Bandwidth, noise & linearity in the receiver
4. Real-time data rate processing capability
5. Spectral efficiency (bit/s/Hz)
6. System capacity (Gbps×km)

For more information see doc. IEEE 802.15-18-0518-00-0thz
In the following presentations …

…we will provide a more detailed overview on three research activities covering:

– CMOS for THz
– Forward Error Correction for the Tbps age
– Seamless integration of fibre with THz wireless
Silicon CMOS Transceiver for Terahertz Wireless Communication

Akifumi Kasamatsu#1, Shinsuke Hara#1, Kyoya Takano#2, Kosuke Katayama#2, Ruibing Dong#2, Sangyeop Lee#2, Issei Watanabe#1, Norihiko Sekine#1, Junji Sato#3, Takeshi Yoshida#2, Shuhei Amakawa#2, Minoru Fujishima#2

#1 National Institute of Information and Communications Technology
#2 Hiroshima University
#3 Panasonic
Challenge of 300-GHz CMOS transceiver

- PA- and LNA-less architecture because of low $f_{\text{max}}$
- High data rate with multi-level signals (QPSK, QAMs) for high speed wireless communication

Developed 300-GHz transceivers in 40-nm Si CMOS process with $f_{\text{max}} \approx 280\text{GHz}$ in collaboration with Hiroshima Univ., Panasonic, and NICT.

Key technology for CMOS transmitter

- Gate-pumped Mixer (Square-Mixer)
  - Square-Mixer is essentially a doubler.
  - IF\(_2\) and LO signals are injected into the gate of the FET mixer.
    Up-converted IF\(_2\) signal using LO is generated.
    Relatively high output power, good linearity -> RF signal

- Image suppression and LO leak cancellation systems

\[
(LO + IF_2)^2 - (LO - IF_2)^2 = 4LO \cdot IF_2
\]

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\[
(LO + IF_2)^2 - (LO - IF_2)^2 = 4LO \cdot IF_2
\]


Akifumi Kasamatsu, NICT
300-GHz CMOS transmitter

- Schematic, chip micrograph, and measured performance of the 300-GHz CMOS transmitter

Pout: $-5.5$ dBm
RF Freq.: 289 - 311 GHz
3-dB BW: 22 GHz

Demonstration of Tx chip

<table>
<thead>
<tr>
<th>Modulation</th>
<th>32QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constellation (Equalized)</td>
<td></td>
</tr>
<tr>
<td>EVM</td>
<td>8.9%</td>
</tr>
<tr>
<td>Data rate</td>
<td>105 Gb/s</td>
</tr>
</tbody>
</table>

Achieved a highest data rate of 105 Gbit/s with 32QAM

300-GHz CMOS receiver

- Schematic, chip micrograph, and measured performance of the 300-GHz CMOS receiver

![Diagram of 300-GHz CMOS receiver]

- LO multiplier chain
  - Double-rat-race splitter
  - Rat-race balun
  - IF
  - LO
  - RF
  - Double balanced fundamental-mixer

(Generating high LO power)

- CG peak: –19.5 dB
- Noise figure: 27 dB
- 3-dB BW: 26.5 GHz

### Wireless performance with TX and RX chips

<table>
<thead>
<tr>
<th>Constellation (Equalized)</th>
<th>QPSK</th>
<th>16-QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM</td>
<td>19.0%rms</td>
<td>12.2%rms</td>
</tr>
<tr>
<td>BER</td>
<td>7.1 x 10^{-8}</td>
<td>9.3 x 10^{-5}</td>
</tr>
<tr>
<td>Sym. rate</td>
<td>14 Gbaud</td>
<td>8 Gbaud</td>
</tr>
<tr>
<td>Data rate</td>
<td>28 Gbit/s</td>
<td>32 Gbit/s</td>
</tr>
</tbody>
</table>

- Achieved a wireless data rate of 32 Gbit/s
- For practical use, CMOS TX and RX chip must be packaged and modularized.

300-GHz CMOS TX and RX modules

- CMOS-chip-to-waveguide transition integrated into a low-cost multilayered glass epoxy PCB

**Structure of the module PCB**

**GCPW-to-WG transition**

**Vertical hollow (depth: λ/4)**

**Back short**

**GCPW-to-WG transition**

**To GSG pads (on CMOS chip)**

Achieved a wireless data rate of 48 Gbit/s with 16-QAM.

Performance of RX module and wireless link

Achieved a wireless data rate of 20 Gbit/s with 16-QAM


Akifumi Kasamatsu, NICT
Towards Ultra-High Throughput FEC Design: EPIC Project

Onur Sahin
InterDigital Europe Ltd.

https://epic-h2020.eu/
Exceeding 100 Gb/s Barrier in Wireless Communications

- **Huge available spectrum** potential above 250 GHz to achieve 100 Gb/s and higher throughputs.
  - 252-325 GHz bands already considered under 802.15.3d.
  - Potential bandwidth allocations: 275-450 GHz in WRC 2019 (AI 1.15).

- Substantial progress in **device-level and RF** front-end.
  - THz photonics based RF front-end solutions demonstrate ~100 Gb/s ([1]).
  - 300 GHz Si CMOS transceiver solutions with >100 Gb/s transmitters ([2]).

- **Novel baseband algorithms and architectures** are necessary to enable ultra-high throughputs in THz domain for a wide range of practical use-cases.
  - **FEC** is the most complex and computationally intense component in the baseband chain → A key enabler and challenge for ultra-high throughput/THz communications.
State-of-the-Art FEC for High Throughput Wireless Systems

In existing wireless standards, IEEE 802.11ad*, IEEE 802.15.3d, and 3GPP 5G NR present FEC classes with highest throughput requirements.

- IEEE 802.11ad (Target peak TP: 7 Gb/s)
  - Rate (1/2, 5/8, 3/4, 13/16) LDPC with code-word length 672

- IEEE 802.15.3d (Target peak TP: 100 Gb/s)
  - Rate 14/15 LDPC (1440,1344)
  - Rate 11/15 LDPC (1440,1056)

- 3GPP 5G NR (Target peak TP: 20 Gb/s)
  - Flexible QC-LDPC; 20 Gb/s with rate 8/9 is supported

* 802.11ay amendment (Draft 3.0 stage) targets >20 Gb/s, in addition includes Rate (1/2, 5/8, 3/4, 13/16) LDPC-1344. The decoder architectures are based on 11ad LDPC-672 codes.
State-of-the-Art 802.11ad FEC Implementations: 65/28 nm Silicon [3]

<table>
<thead>
<tr>
<th>Code</th>
<th>Ref.</th>
<th>Code length</th>
<th>Rate support</th>
<th>Process nm</th>
<th>Area mm²</th>
<th>Freq MHz</th>
<th>TP Gb/s</th>
<th>Area eff. Gb/s/mm²</th>
<th>Energy eff. pJ/bit</th>
<th>Power dens. W/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPC</td>
<td>[4]</td>
<td>672</td>
<td>13/16</td>
<td>65</td>
<td>0.16</td>
<td>500</td>
<td>5.6</td>
<td>35</td>
<td>17.65</td>
<td>0.62</td>
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<tr>
<td>LDPC</td>
<td>[5]</td>
<td>672</td>
<td>802.11ad</td>
<td>28</td>
<td>0.78</td>
<td>470</td>
<td>18</td>
<td>23.6</td>
<td>18</td>
<td>0.41</td>
</tr>
<tr>
<td>LDPC</td>
<td>[6] 9 iter</td>
<td>672</td>
<td>13/16</td>
<td>28</td>
<td>2.8</td>
<td>220</td>
<td>160</td>
<td>57.1</td>
<td>6</td>
<td>0.32</td>
</tr>
</tbody>
</table>

- The referenced FEC architecture designs, and several others in the literature, comfortably achieve 802.11ad implementation requirements (throughput, power density, energy efficiency).
- Particular designs (e.g. [6]) achieve 160 Gb/s throughput, yet for a fixed code-rate and code block-length.
- Each design has a different communication performance (BER vs SNR).
State-of-the-Art 802.11ad FEC Implementations: 7 nm Projection [3]

- With 7nm nodes, substantial increase in area efficiency is anticipated.
- Multiple decoder instances of [4], [5], and a few decoder instances in [6] could well-exceed 100 Gb/s throughputs and approach 1 Tb/s.
- However, significant increase in power density is observed.

<table>
<thead>
<tr>
<th>Code</th>
<th>Ref.</th>
<th>Code length</th>
<th>Rate support</th>
<th>Process nm</th>
<th>Area mm²</th>
<th>Freq MHz</th>
<th>TP Gb/s</th>
<th>Area eff. Gb/s/mm²</th>
<th>Energy eff. pJ/bit</th>
<th>Power dens. W/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPC</td>
<td>[4]</td>
<td>672</td>
<td>13/16</td>
<td>7</td>
<td>0.003</td>
<td>2923 1000</td>
<td>32 11</td>
<td>11113 3832</td>
<td>1.9 1.9</td>
<td>21.1 7.2</td>
</tr>
<tr>
<td>LDPC</td>
<td>[5]</td>
<td>672</td>
<td>802.11ad</td>
<td>7</td>
<td>0.07</td>
<td>1410 1000</td>
<td>54 39</td>
<td>830 600</td>
<td>2.24 2.24</td>
<td>3.8 2.7</td>
</tr>
<tr>
<td>LDPC</td>
<td>[6]</td>
<td>672 9 iter</td>
<td>13/16</td>
<td>7</td>
<td>0.2</td>
<td>660.0 480</td>
<td>2057 4100</td>
<td>1.5 0.6</td>
<td>3.1 3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 iter</td>
<td></td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table above provides a comparison of different LDPC implementations with 7nm nodes, showing their code length, rate support, process nm, area, frequency, throughput, area efficiency, energy efficiency, and power density.
Observations on SoA High-throughput FEC Implementation Studies

- SoA implementation studies of 802.11ad LDPC codes demonstrate significant performance gaps in achieving practical ultra-high throughputs (100 Gb/s → Tb/s) **even when taking 7nm performance scaling into account.**
  - Silicon technology evolution to 7nm is expected to provide sufficient area efficiency gain.
  - **Power density will emerge as a binding constraint,** with an initial estimate of 10x-100x performance gap between the practical requirements and SoA FEC in 7nm.
  - **Energy efficiency will also be another constraint** with considerable performance gap.
  - **The clock frequency feasible value of 1 GHz** impose additional constraints on ultra-high throughputs – extreme parallel and unrolled architectures are mandatory.
Practical Tb/s FEC Implementation KPI Bounds – EPIC Project

New generation of FEC technology to enable ultra-high throughput (Tb/s) wireless communications in 7nm silicon.

- Satisfy stringent communications performance (BER $10^{-6}$ to $10^{-12}$) and flexibility requirements (in terms of e.g. code rates, block length)
- Focus on: Turbo Codes, LDPC Codes, and Polar Codes.

<table>
<thead>
<tr>
<th>EPIC FEC KPI bounds</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Area limit</td>
<td>10 mm²</td>
</tr>
<tr>
<td>Area efficiency limit</td>
<td>100 Gb/s/mm²</td>
</tr>
<tr>
<td>Energy efficiency limit</td>
<td>~1 pJ/bit</td>
</tr>
<tr>
<td>Power density limit</td>
<td>0.1 W/mm²</td>
</tr>
</tbody>
</table>

- FEC decoder **throughput**: 1 Tb/s
- Practical FEC IP **area constraint** on a SoC: 10 mm²
- FEC IP **power budget** to avoid heat removal issues: ~1 W
Where We are Today in EPIC Project
towards 1 Tb/s [7]

**Overview on Implementation Properties**

<table>
<thead>
<tr>
<th>Code</th>
<th>Decoding algorithms</th>
<th>Parallel vs. serial</th>
<th>Locality</th>
<th>Compute kernels</th>
<th>Transfers vs. compute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo code</td>
<td>MAP</td>
<td>serial/iterative</td>
<td>low</td>
<td>Add-Compare-select</td>
<td>compute dominated balanced</td>
</tr>
<tr>
<td>LDPC code</td>
<td>Belief propagation</td>
<td>serial/iterative</td>
<td>(interleaver)</td>
<td>Min-Sum/add</td>
<td></td>
</tr>
<tr>
<td>Polar code</td>
<td>Successive cancelation/</td>
<td>parallel/iterative</td>
<td>low (Tanner graph)</td>
<td>Min-Sum/add/sorting</td>
<td></td>
</tr>
</tbody>
</table>

**28nm low V_t FDSOI Technology, worst case PVT, after Place & Route**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo code (4 iter)</td>
<td>128</td>
<td>1/3</td>
<td>800</td>
<td>102</td>
<td>23.6</td>
<td>-</td>
<td>4.34</td>
<td>-</td>
</tr>
<tr>
<td>LDPC code (9 iter)</td>
<td>672</td>
<td>13/16</td>
<td>400</td>
<td>268</td>
<td>2.8</td>
<td>1500</td>
<td>95.7</td>
<td>5.6</td>
</tr>
<tr>
<td>LDPC code (4 iter)</td>
<td>672</td>
<td>13/16</td>
<td>400</td>
<td>268</td>
<td>1.3</td>
<td>700</td>
<td>215</td>
<td>2.5</td>
</tr>
<tr>
<td>Polar code</td>
<td>1024</td>
<td>1/2</td>
<td>746</td>
<td>764</td>
<td>2.95</td>
<td>3300</td>
<td>259</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Fig. 1. 102 Gbit/s Turbo code decoder, area 23.01 mm²
Fig. 2. 268 Gbit/s LDPC code decoder, area 2.8 mm²
Fig. 3. 764 Gbit/s Polar code decoder, area 2.95 mm²
Challenges for Tb/s Throughput Decoders

Architectural approach
- “Unrolling” of iterations (Turbo Code MAP, LDPC belief propagation).
- “Flattening” of Polar Factor Tree traversal (SC algorithm).
- Heavy pipelining and spatial parallelism.

Good news
- Throughputs beyond 100 Gbit/s are feasible for all three code classes.

Bad news
- Limited to small block sizes (all three codes) and small number of iterations (Turbo, LDPC) → degrades the communications performance.
- Suffers from limited flexibility in block lengths (all three codes), varying number of iterations (Turbo, LDPC) and code rate flexibility (LDPC, Polar).
- Pipelining increases the latency.
- Power density in the order of 1 W/mm² is far too high for air-cooled package.
Observations for Tb/s Throughput Decoders

**Comparison related to implementation efficiency**
- LDPC and Polar code decoders have similar implementation efficiencies.

**Communications performance matters!**
- Depends on code, block length, code rate and decoding algorithm.
- Code impacts decoder complexity; e.g. position of frozen bits for Polar code decoder, structure of H matrix for LDPC code decoding.

⇒ A comparison based only on communication performance makes just as little sense as a comparison only on implementation level.
⇒ Communication and implementation performance have to be jointly considered.
Design Trade-Offs for Efficient Design

- $V_{dd}$ downscaling of high throughput decoders $\rightarrow$ Decreases throughput but largely improves energy efficiency.

- Decrease decoder parallelism for LDPC belief propagation algorithm $\rightarrow$ Decreases throughput but improves flexibility.

- More complex decoding algorithms: E.g. SCL for Polar code decoding $\rightarrow$ Improves communications performance, but decreases throughput, area and energy efficiency.

- Hybrid decoders and concatenated codes: Combination of high throughput and high performance decoders, e.g. Majority-Logic and successive cancellation in Polar codes, inner and outer codes.
Communications Performance
Comparison: LDPC vs Polar Codes

- FEC classes evaluated:
  - **802.15.3d LDPC**: Length-1440, Rate=11/15.
  - **Polar codes**: Length(L) = 2048, 4096, Rate=11/15. List-size=1,2 (CRC=8bits). Density (D) evolution based code design.

**Observation:**
- Polar code L=4096, List-size=1 and Polar code L=2048, List-size=2 are able to compete with LDPC codes at SNRs greater than 6dB.
- LDPC code experiences degraded performance at high SNRs (>6dB), a critical range for THz use-cases.

- Modulation: QPSK
- AWGN channel (BH/FH use-case in 802.15.3d study)
Conclusion

- New baseband and FEC solutions are necessary to materialize practical ultra-high throughput (>100 Gb/s) THz communications.

- Progress made in 100 Gb/s → 1 Tb/s LDPC and Polar code implementations within THz use-cases practicality constraints.
  - Challenges remain including relatively small block lengths, number of iterations (LDPC and Turbo), and low code flexibility.
  - Power density is a key issue in ultra-high throughput THz!

- A joint study of the two domains, which is often done independently, is mandatory for ultra-high throughput THz communications:
  - New and improved code design with better communications performance
  - FEC architecture design satisfying THz implementation requirements

- The standard 802.15.3d codes lack a detailed implementation study in the literature. A necessary next step to explore their potentials.
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REFERENCES


Integration of fiber-optics/THz technologies

Colja Schubert, Robert Elschner, Carlos Castro

Fraunhofer Heinrich Hertz Institute
Tutorial THz Communications

November 2018
Introduction

- THz bandwidth is adequate to fit contemporary optical transponder solutions → 100/200 Gb/s
- Main question: how can optics and THz technologies be integrated?
Network scenarios
System architectures

- Indoor quasi-omnidirectional
- Point-to-Point
- Point-to-Multipoint
Point-to-point systems

- Stationary/static outdoor connections that require to cover long distances and to support large data rates

- **Target**: 1 Tb/s over 1 km wireless link
# Optical transceivers

<table>
<thead>
<tr>
<th>Aspect</th>
<th>CFP</th>
<th>CFP2</th>
<th>CFP8</th>
<th>QSFP28</th>
<th>QSFP-DD</th>
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</thead>
<tbody>
<tr>
<td>W x L x H [mm]</td>
<td>82 x 145 x 14</td>
<td>41.5 x 106 x 12.4</td>
<td>40 x 102 x 9.5</td>
<td>18.4 x 72 x 8.5</td>
<td>18.35 x 58.26 x 8.5</td>
</tr>
<tr>
<td>Power Class</td>
<td>8 W</td>
<td>3 W</td>
<td>4 W</td>
<td>1.5 W</td>
<td>1.5 W</td>
</tr>
<tr>
<td></td>
<td>16 W</td>
<td>6 W</td>
<td>8 W</td>
<td>2 W</td>
<td>3.5 W</td>
</tr>
<tr>
<td></td>
<td>24 W</td>
<td>9 W</td>
<td>12 W</td>
<td>2.5 W</td>
<td>7.0 W</td>
</tr>
<tr>
<td></td>
<td>32 W</td>
<td>12 W</td>
<td>16 W</td>
<td>3.5 W</td>
<td>8.0 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 W</td>
<td>20 W</td>
<td>4 W</td>
<td>10 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18 W</td>
<td>24 W</td>
<td>4.5 W</td>
<td>12 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 W</td>
<td>14 W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt; 14 W</td>
</tr>
<tr>
<td>Electrical interface</td>
<td>148 pins</td>
<td>104 pins</td>
<td>124 pins</td>
<td>38 pins</td>
<td>76 pins</td>
</tr>
<tr>
<td></td>
<td>10x10G / 4x25G</td>
<td>10x10G / 4x25G</td>
<td>16x25G / 8x50G / 4x100G</td>
<td>4x25G</td>
<td>8x25G / 8x50G</td>
</tr>
<tr>
<td>Application</td>
<td>C-band DCO</td>
<td>C-band ACO</td>
<td>Reach: from tens of meters to thousands of meters</td>
<td>CWDM4: 4λ x 2km</td>
<td>SR: tens of meters</td>
</tr>
<tr>
<td></td>
<td>100G Single carrier for metro/long-haul</td>
<td>100G → 200G</td>
<td>Equipment interconnection</td>
<td>10G LR: 10 km</td>
<td>Data center intra- connect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reach: tens of meters to couple of kms</td>
<td>E standard: 40 km</td>
<td>SR: tens of meters</td>
<td></td>
</tr>
</tbody>
</table>
Digital systems

- Intensity modulation/Direct detection (IM/DD) systems
  Information is encoded in different amplitude levels, which are detected by a simple photodiode at Rx
- Subsystems (links) are recognizable along the transmission line

- Advantages: cost-effective
- Disadvantages: reach and data rate

- Most common form-factors: SFP+, QSFP28, XFP, CFP2
Digital system configuration

- Multiple QSFP modules act as interfaces between optics and THz
- Media converter (MC) aggregates channels → TDM/FDM
- Data rates: 10 Gb/s → 200 Gb/s
- Challenges: compliance of the media converter with the channel specification (client-side interfaces)
Coherent transmission systems

• Coherent detection is a technique that involves encoding the data both in the amplitude and phase of the optical signal

• Advantages: high spectral efficiency, high data rates, and superior performance

• Disadvantages: more expensive than IM/DD transmission

• Form-factors that currently support coherent transmission are CFP/CFP2 (either DCO or ACO)
Coherent system configuration

- Standard CFP2-ACO modules act as interfaces between optical and electrical domains
- Transparency of the THz link ('fiber extension')
- Data rates: 100 Gb/s → 500 Gb/s
- Challenges: joint impairment mitigation → phase noise, I/Q imbalances, SNR

Good bet to reach the target 1 Tb/s transmission
# Overview system configurations

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Coherent systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital systems</td>
<td>Coherent systems</td>
</tr>
<tr>
<td>Simple transceiver design</td>
<td>“High” data rates (100-500 Gb/s)</td>
</tr>
<tr>
<td>Adjustments based on link conditions</td>
<td>Long-haul optical transmission is possible</td>
</tr>
<tr>
<td>Cost-effective</td>
<td>Improved performance (DSP)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>Digital systems</th>
<th>Coherent systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short optical distances</td>
<td>Joint impairment mitigation</td>
<td></td>
</tr>
<tr>
<td>“Low” data rates (10-200 Gb/s)</td>
<td>Transparent system doesn’t allow to adjust transmission parameters</td>
<td></td>
</tr>
<tr>
<td>Interaction media converter/client-side interface</td>
<td>More expensive and complicated systems</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- Applications can be summarized in three large groups: indoor quasi-omnidirectional, point-to-multipoint, and point-to-point

- Interface between the optical domain and the THz elements is critical for a seamless integration of these technologies in the existing communication networks

- There are different approaches to construct an optical/THz system: digital configuration and coherent configuration

- Currently in the process of investigating THz transmission in combination with optical components
Conclusions and Outlook

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Conclusions

• Frequency bands beyond 275 GHz offer a huge potential to implement wireless communication systems with data rates targeting of more than 100 Gbit/s
• A first 300 GHz standard @ IEEE 802 has been completed in 2017
• Activities targeting allocation of spectrum beyond 275 GHz at WRC 2019 (AI 1.15)
• Ongoing projects towards THz Communications are covering the whole range from Semiconductor Technology (e.g. CMOS) to Physical Layer improvement (e.g. FEC) and Networking (e.g. integration of fibre with THz links)

_ THz Communications is a real option for wireless networks beyond 5G!_
Outlook for IEEE 802 Standardisation

- The THz frequency range may provide various opportunities for the development of further standards or amendments targeting beyond 5G networks

- Examples are standards covering
  - Applications requiring beamforming
  - Systems targeting data rates in Tbps range
  - Seamless integration of fibre with THz wireless links