Can Graphene drive the further evolution of communication systems?

Wolfgang Templ, Nokia Bell-Labs
19/12/018
A New Networking & Connectivity Era

- Discover (Information)
- Share (Media)
- Sell (Media)
- Share (Personal)
- Automate (Everything)

- 4.3 ZB/Yr: Connected Everything + Contextual Automated Experiences
- 2.6 ZB/Yr: 8K Video + Cloud Hosting User-Generated Content
- 1.0 ZB/Yr: Mosaic
Telecommunication Driving Trends

Cost per GB [NA]

Mobile data usage per device [GB per month]

Source: Bell Labs Consulting
Network Vision 2020

Sensor Devices
2014: <1Mbps
2020: <1M, 1G...10G

RF
1Gbps
Proximity
10Gbps

mm-Wave
10Gbps

FTTX
100Gbps

Metro
1Tbps

Backbone/Routers
10Tbps

Data Rate

2014
0.01G...0.1G

0.2G...10G

10G...100G

1 T

10...100G

10 T

1 T

Nodes

10⁹...10¹¹

10⁶...10⁹

10⁴...10⁵

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Application Fields

Communication Infrastructure Gear
- Moderate volumes
- Very high performance requirements
- Very high reliability requirements
- More Moore + More Than Moore

User Equipment, Terminals, ONUs
- Consumer market, high volumes
- Very high integration (+Sensors)
- Short life cycle
- Dominated by More Moore
- Increasing performance
The Six Essential 5G Technologies

**Massive MIMO**
- Higher spectral efficiency through spatial multiplexing (beamforming)
  - ~5X increase in spectral efficiency

**New Virtualized + Software-Defined Core**
- For flexible routing through centralized, distributed, gateways optimized for any service mix

**Multi-RAT**
- With network controlled traffic steering and cell-less architecture
  - ~2X increase data rate
  - Guaranteed user/service experience

**New ”mmWave” spectrum**
- Small cells
  - ~10X bandwidth

**Modular Framing Structure**
- For ultra-broadband, ultra-narrowband and ultra-low latency support

**New Air Interface**
- New Waveform and control for flexible multi-service interface
  - ~2X battery life
  - ~5X lower latency

**New Spectrum**

**New Core**

**New Air Interface**

**New Core**

**Multi-RAT**

**Massive MIMO**

**5G**
5G Target Requirements

- "Unlimited experience" with 100 Mbps peak data rates whenever needed
- 1,000,000 devices per km²
- Ultra low cost for massive machine communications
- 10 years on battery
- "For everything"
- "Instant action"
- 1,000 x more traffic
- <1 ms radio latency
- Ultra reliability < 10⁻⁵ E2E outage
- Zero mobility interruption
The Simple Formula: $5G = R1 + R2 + R3 + R4$

Ultra-broadband: “VR/AR”

Ultra-low latency: “System Control”

Forbidden region: Shannon Limit

Today: “Voice, Data, Video”

Ultra-narrowband: “Things”

F. Boccardi, Bell Labs, IEEE Comms. Magazine, 201402
Fixed Access
Convergence at 10Gbps

- ~1 Gbps peak rates per household
- ~100 Mbps sustained data rates per household
- Self-installable CPE
5G as well imposes requirements to optical communication
Datacom Optical Transport
Application Scenarios

**Intra datacenter**
- Different transmission distances up to 2 km
- Multiple fiber instead of WDM
- 100G Ethernet is well established standard
- 400GbE is coming, standard settled, different products introduced
- 400G relies on multiplex
  - NRZ or PAM4
  - DML, EML (Direct – vs. EA modulated Laser)
  - O-band (1300 nm) and C-band (1550 nm)

**Inter datacenter**
- Target 80 km up to 120 km
- Optical amplification for WDM at Tx or Rx
- C-band (1550 nm)
- Solutions
  - Coherent, DWDM 400G ZR: 400G/l
  - Direct detect PAM4: 50G/l, optical CD compensation
100G/400G coherent optical interface
Electrical IQ-Modulation

E.g. 16QAM Polarisation Multiplex:
• Adding \textit{two} optical polarisations (in the PBC);
  \textbf{per polarisation}:
  \begin{itemize}
  \item 4 bits coded into 1 symbol (i.e. 2 in In-Phase (I) and 2 in Quadrature (Q) component)
    \Rightarrow \text{Modulator is driven by electrical four-level signal}
  \item After 90° phase rotation optical Q-signal is superposed with I-signal
  \end{itemize}
• 4 bits transmitted per symbol interval
• Def. Symbol rate: 1 Symbol/s = 1 baud
• 1 baud = 4 bit/s
• 64 Gbaud = 256 Gbit/s
• Using both polarisations 512 Gbit/s (incl. FEC overhead)

DAC-I/DAC-Q Synchronisation: <800 fs
Datacom optical transport
Research Topics

• Coherent systems for inter and intra datacenter
• @400G and beyond coherent technology could be advantageous due to
  • Lower power consumption and DSP complexity
  • 4 dimensional modulation per λ (I and Q of QAM symbol and 2 polarizations)
  • Cost due to lean optics
  • Maturity of coherent technology
• What’s beyond 400G?
  – Further increase of rates expected
    • Possible rates are 800G/1T/1.6T/4T
    • Work towards standardization has not started yet
    • 800G could be single λ, the other options require multiplex
System setup and power budget for low cost coherent Solution

- One laser per link (sharing of laser for Tx and Rx)
- No optical amplification in single carrier (single l)
- Rx with integrated frontend including TIA

LiNb: $IL_{MOD} \approx 20\text{dB...30dB}$

Photodiodes: $R \approx 0.5 \text{ A/W}$
Coherent Technology for Long Haul Optical Transport
Components-Status

- **Modulator**
  - LiNb has a -3db bandwidth of 40 GHz, almost constant frequency slope (Drive voltage ~4V)
  - InP upper frequency limits operation to symbol rates <80 Gbaud (V_D~2..2.5V)
  - Graphene has been demonstrated with almost flat frequency response up to 60 GHz (V_D <=1V)
  - SiGe / Ge tighter limits regarding frequency

- **Receiver**
  - InP is classical receiver material, upper frequency limit up to 100 GHz demonstrated, trade off bandwidth – responsivity (up to 1A/W (not hispeed); >0.1A/W (for hispeed)
  - SiGe / Ge lower frequency limits
  - Graphene flat response up to 60 GHz has been reported in literature
Tera-bit coherent optics

- Advanced modulation formats by ADC/DAC ASICS enable high data rates with high spectral efficiency
- Need high performance optics and analog ASICs - TIA, driver
  - Wide bandwidth and linearity
  - Low power linear analog amplifiers
- Power consumption is the real limitation for footprint reduction

Graphene photonics may change the paradigm. It potentially allows to get rid of high performance power hungry analog ASICs.

It enables high density integration of multiple functions in a small form factor.

Baud rate growth from 32.5Gbps -> 40Gbps -> 56Gbps

Baud rate 32.5Gbps
... and here comes Graphene into the game
Graphene – Material Properties / Component FOMs

- RT carrier mobility, \((e^- / h^+): 200000/200000\)
  - Limited to 40000 cm\(^2\)V\(^{-1}\)s\(^{-1}\) by optical phonon scattering on SiO\(_2\) substrate; Si: 1400/450 \((e^- / h^+)\) cm\(^2\)V\(^{-1}\)s\(^{-1}\)
  - Competitive modulation, detection and switching performance for mobilities >10000 cm\(^2\)V\(^{-1}\)s\(^{-1}\), carrier conc. \(\sim 10^{12}\) cm\(^{-2}\)

- DC Resistivity: \(1 \cdot 10^{-6}\) \((\text{Cu}: 1.6 \cdot 10^{-2})\) Ωcm

- Thermal conductivity: \(\sim 5 \cdot 10^3\) \((\text{Cu}: 401)\) Wm\(^{-1}\)K\(^{-1}\)

- Optical transmission @\((0.5-1.2)\)eV: 97.7%;
  - Tunable by electric gating

- Nearly ballistic \(e^-\) transport
  - High electrical and thermal conductivity, transparency, tunable band gap

- Complex Conductivity \(\sigma_g = (\sigma_{g,r} + i \sigma_{g,i}) = F(\omega, \Gamma, \mu_C, T, ...)\)
  - Electronic control of conductivity

- Tunable Bandgap

<table>
<thead>
<tr>
<th>Material</th>
<th>(V_L (\text{V mm}))</th>
<th>Insertion loss (dB mm(^{-1}))</th>
<th>FOM(_{PM}) (V dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO(_3) (E)</td>
<td>50–100</td>
<td>0.4</td>
<td>20–40</td>
</tr>
<tr>
<td>LiNbO(_3) (E)(^a)</td>
<td>18</td>
<td>0.3</td>
<td>5.4</td>
</tr>
<tr>
<td>InGaAsP/InP (E)</td>
<td>5–10</td>
<td>0.7</td>
<td>3.5–7</td>
</tr>
<tr>
<td>Si photonics (E)</td>
<td>10–20</td>
<td>1–2</td>
<td>10–20</td>
</tr>
<tr>
<td>Graphene (T)</td>
<td>(0.7–2.8)</td>
<td>0.1–1.2</td>
<td>1–2</td>
</tr>
</tbody>
</table>

**MZI Modulator Performance:**

Integrated Photonics Technology

<table>
<thead>
<tr>
<th>Silicon photonics</th>
<th>Graphene photonics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td><strong>Technology</strong></td>
</tr>
<tr>
<td>• Active photonic circuit</td>
<td>• Passive photonic circuit</td>
</tr>
<tr>
<td>• Implantation needed</td>
<td>• No implantation</td>
</tr>
<tr>
<td>• Ge epitaxy</td>
<td>• No epitaxy</td>
</tr>
<tr>
<td><strong>Approaches to functionalities</strong></td>
<td><strong>Approaches to functionalities</strong></td>
</tr>
<tr>
<td>• Free carrier effect</td>
<td>• Capacitive effect</td>
</tr>
<tr>
<td>• Thermo-optic effect</td>
<td>• Thermo-optic effect</td>
</tr>
</tbody>
</table>

![Silicon photonics diagram](image1)

![Graphene photonics diagram](image2)
## Photonic devices

<table>
<thead>
<tr>
<th>Silicon photonic devices</th>
<th>Graphene photonic devices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulators</strong></td>
<td><strong>Modulators</strong></td>
</tr>
<tr>
<td>• Electro-absorption (Franz Keldish)</td>
<td>• Electro-absorption</td>
</tr>
<tr>
<td>- SiGe alloys</td>
<td>- Graphene capacitor</td>
</tr>
<tr>
<td>- Wavelength selective</td>
<td>- Broadband</td>
</tr>
<tr>
<td>• Phase</td>
<td>• Phase</td>
</tr>
<tr>
<td>- Free carrier</td>
<td>- Graphene capacitor</td>
</tr>
<tr>
<td>- FOM &gt; 10dBV</td>
<td>- FOM &lt; 10dBV (including loss)</td>
</tr>
<tr>
<td><strong>Switches</strong></td>
<td><strong>Switches</strong></td>
</tr>
<tr>
<td>• Thermo-optic switch</td>
<td>• Capacitive switch</td>
</tr>
<tr>
<td>- Joule effect</td>
<td>- Capacitive effect</td>
</tr>
<tr>
<td>- High static power consumption</td>
<td>- No static power consumption</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td><strong>Detector</strong></td>
</tr>
<tr>
<td>• Ge on Si</td>
<td>• Photoconductor, Schottky on Si, AC photodiode</td>
</tr>
<tr>
<td>- High responsivity</td>
<td>- Low responsivity</td>
</tr>
<tr>
<td>- High speed</td>
<td>- High speed</td>
</tr>
</tbody>
</table>
FIRST STEPS:
50Gbps PHOTO DETECTOR ON Si-WAVEGUIDE (AMO GMBH, ALCATEL-LUCENT)

• Graphene Photodiodes (GPDs)
  • Broadband light absorption (FIR to UV)
  • Ultrahigh carrier mobilities
  • Can be integrated on Si on wafer-scale
  • PV effect at Graphene /metal interface
    • -> Bias free operation
    • No dark current
    • Intrinsic operation speed up to 640 GHz
    • Internal quantum efficiency of 30%-60%

• CVD grown Graphene on Si waveguides
• Operating in C-Band (λ=1550 nm)
• Lin. Iph(Popt) characteristic w.o. saturation
• -3dB-Bandwidth = 41 GHz
  (limited by measurement setup and device parasitics)

Schematic of the heterodyne measurement setup, and frequency response of the relative PD output power with a -3 dB roll off frequency at 41 GHz (blue); RC low pass with a -3 dB frequency of 41 GHz (red).

From “50 GBit/s Photodetectors Based on Wafer-Scale Graphene for Integrated Silicon Photonic Communication Systems”, D. Schall, D. Neumaier, W. Kuebart, B. Junginger, W. Templ, ACS Photonics, 2014 1 (9);
Transmission Performance Measurement

- GPD inserted into optical 12.5 Gbit/s link
- Bit Sequence NRZ-OOK via LiNbO3 Modulator
- \( \lambda = 1550 \) nm, 17dbm (EDFA)

Photo response at GPD (still insufficient)

- Zero bias: \( V_{out} = 0.4 \) mVpp, but SNR is insufficient for data transmission
- 1.6 V bias: \( V_{out} \) increased by a factor of 4
- Further linear increase to higher responses with bias
- Open eye-diagram proving successful transmission of \( n = 2^{31} - 1 \) pseudo-random bit sequence (PRBS) at 12.5 GBit/s.
50Gbps Photo Detector on Si-Waveguide

- 50Gbit/s Transmission Performance Measurement
  - 50 Gbit/s NRZ-OOK signal generated by four 12.5Gbit/s streams driving LiNbO₃ modulator
  - \( \lambda = 1550 \text{ nm}, 17.6 \text{dbm (EDFA)} \)

- Photo response at GPD
  - Bit stream detected with 70 GHz scope; (averaging); no bias at GPD i.o. to avoid side effects
  - Excellent signal integrity
  - \( T_{\text{rise}} \), (10% to 90%) = 9 ps, i.e. BW = 39 GHz

Parts of this work have been performed in cooperation between AMO GmbH and Alcatel-Lucent Bell Labs within frame of European Flagship Graphene (604391)
HETERO INTEGRATION – GRAPHENE ON SILICON

Motivation for Co-integrating Graphene on Silicon

• Cost efficiency
• Opening the path for single chip integration of Si-and Graphene based devices
• Enabling high-integrated photonic subsystems
• High signal- and data processing capability (Silicon)
• Single chip integration avoiding need for highspeed interfaces
• Reduction of module cost (packaging effort)
Vision: Integrated high Performance Optical TRX PIC
Long Term Goal: 400Gbps Optical Transceiver – Photonic SIP

- Graphene based high BW photo detector array
  - replacing electrical interface by photonic one-

- TIA & signal conditioning (equalizer)
- 2 HiSpeed DACs (SiGe BiCMOS or CMOS)
- Memory
- 2 Modulator drivers
- Graphene based modulators
- Graphene based optical 90°-phase shifter

- Critical:
  - Speed performance/bandwidth
  - Power consumption / thermal management
  - Mounting/assembly (esp. optical coupling/link)
    - Observe automated production (positioning?)

- Total Costs !!
Coming true …

Exemplarily Architectures

Double-gated thermoelectric photodetector

Graphene-based transceiver integrated in a Si photonic interposer

CMOS circuit on a SLG photonics circuit

Graphene-based integrated photonics for next-generation datacom and telecom.
M. Romagnoli et al., Nat. Rev. Mat., 3, 392-414/2018
GRAPHENE Spearhead Projects

• Target: Graphene based optical transmission system for DC/Metro range
  • Packaged graphene TX and RX
  • Integration in NOKIA eval. board and lab based transmission test
  • Integration in product electronic board with DSP and trial in a NOKIA commercial system

• OE components for replacement in coherent systems
  – IQ modulator and coherent receiver

• Critical Parameters [desirable values]
  – Modulator
    • Modulation index, Bandwidth [>45GHz] and insertion loss [<7db] of photonic chip including fiber – chip transitions
  – Receiver
    • Sensitivity [0.5 A/W], Bandwidth [100GHz], dark current [few nA], losses of chip and fiber – chip coupling
    • C- and L-Band Operation