NOKIA Bell Labs

# Can Graphene drive the further evolution of communication systems?

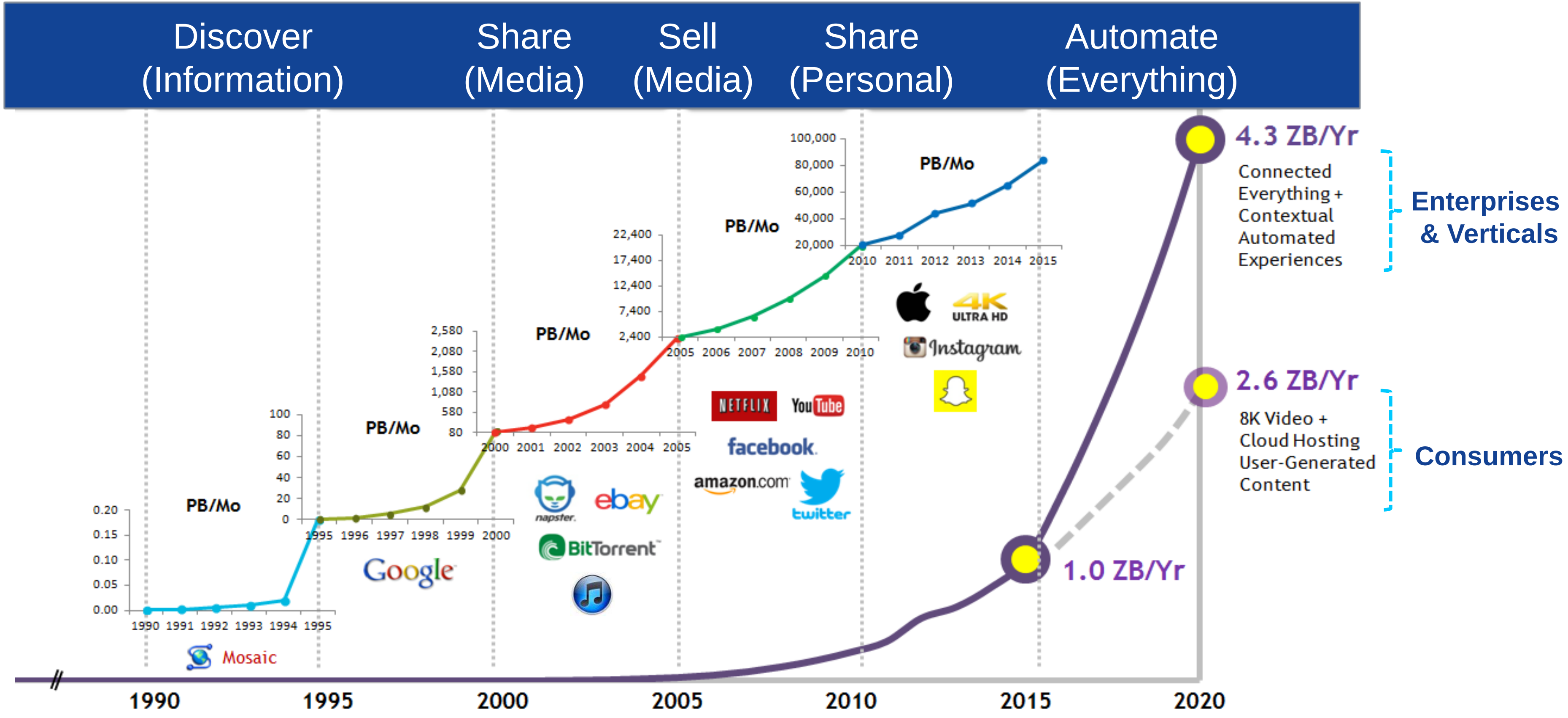
Wolfgang Templ, Nokia Bell-Labs

19/12/018

GRAPHENE FLAGSHIP

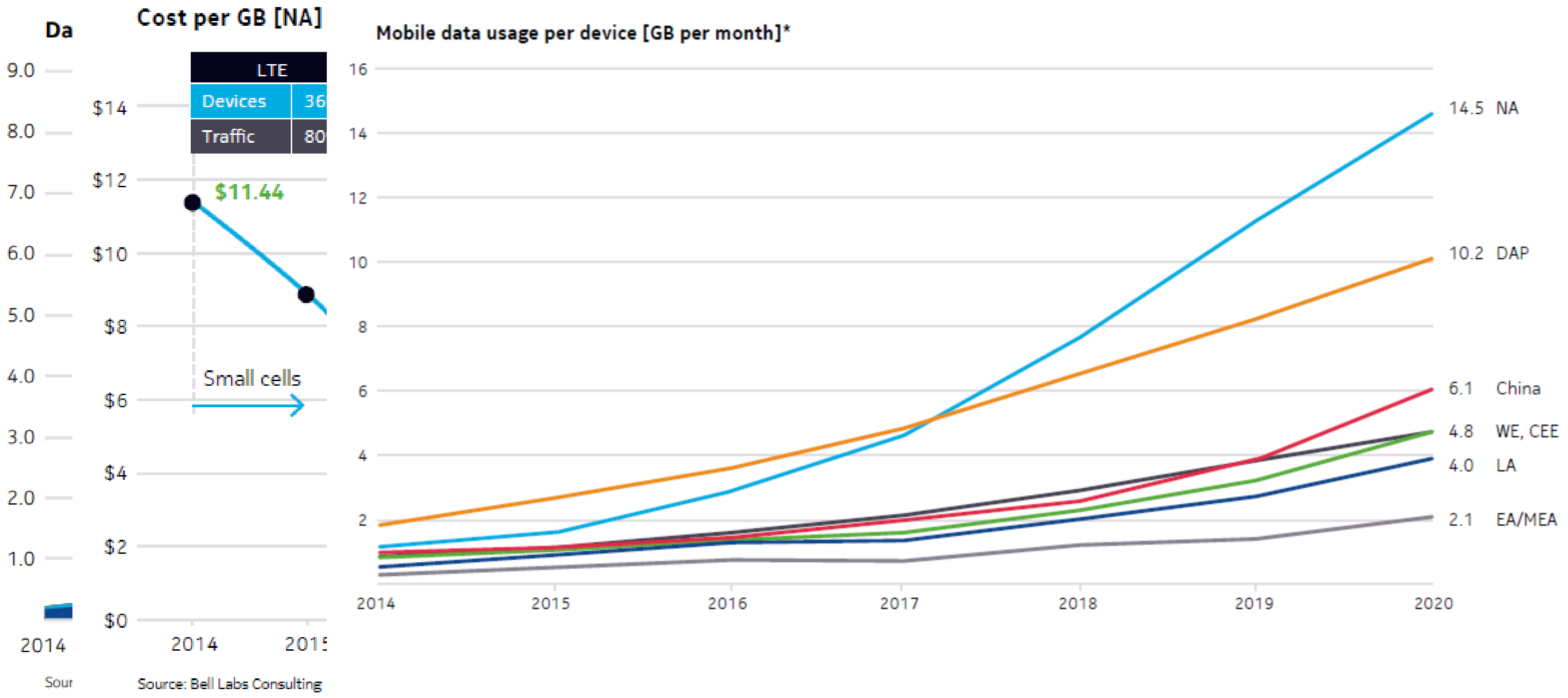
  <public>

# A New Networking & Connectivity Era




  <public> NOKIA Bell Labs

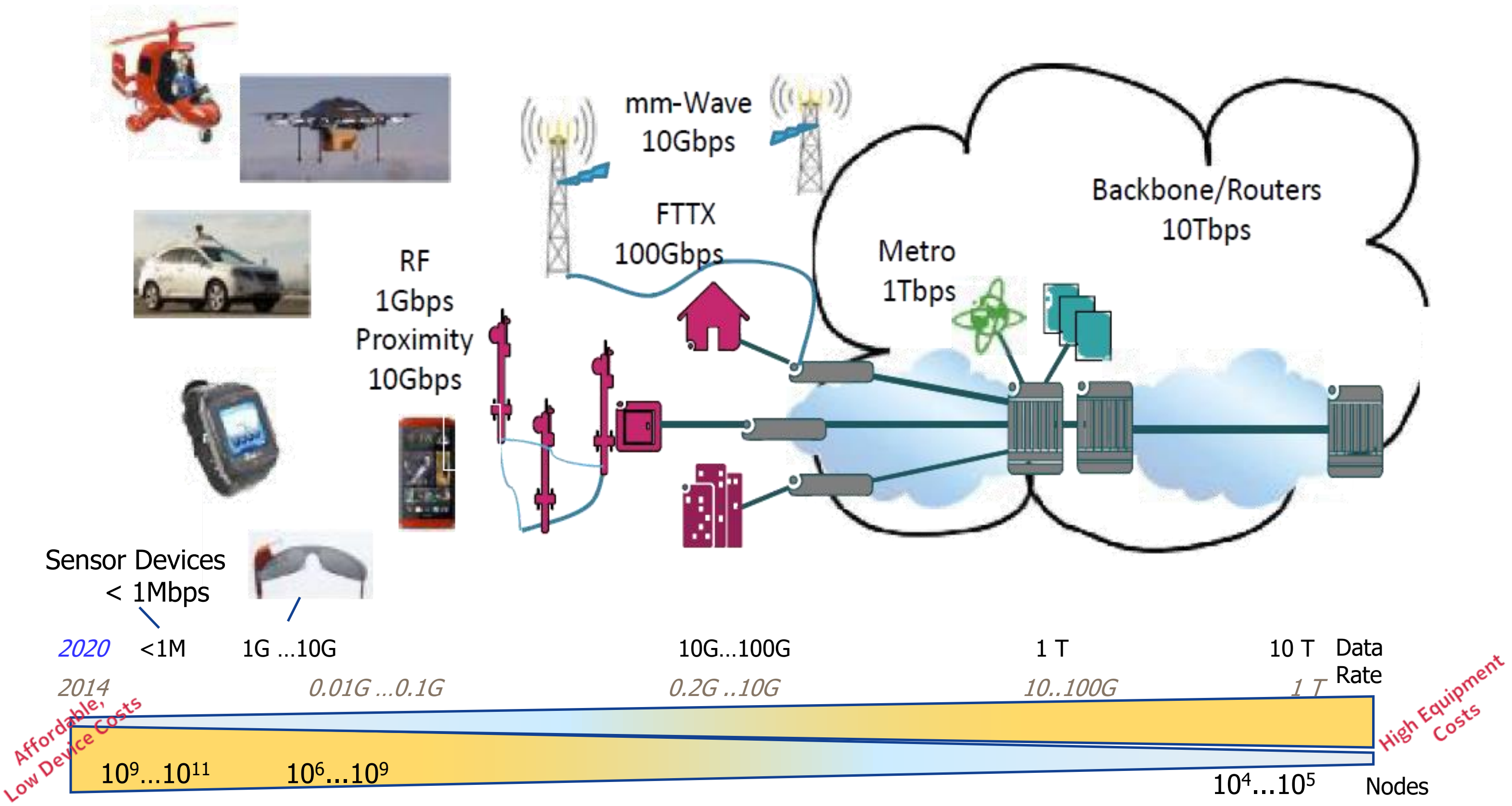
# Telecommunication Driving Trends






<public>
NOKIA Bell Labs

# Network Vision 2020




  <public> NOKIA

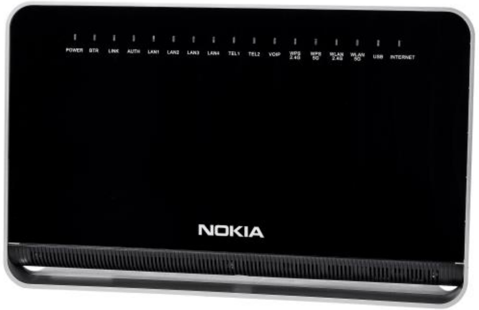
# Application Fields

## Communication Infrastructure Gear

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


## User Equipment, Terminals, ONUs

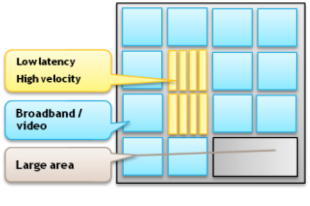
- Consumer market, high volumes
- Very high integration (+Sensors)
- Short life cycle
- Dominated by More Moore
- Increasing performance


  <public> NOKIA Bell Labs

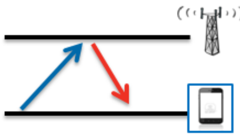
# The Six Essential 5G Technologies

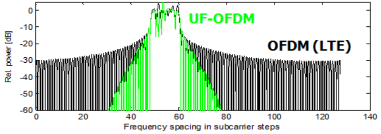
**Modular Framing Structure** for ultra-broadband, ultra-narrowband and ultra-low latency support

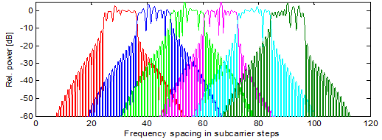



**New Air Interface:** New Waveform and control for flexible multi-service interface

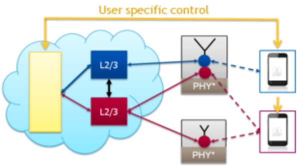
- ~2X battery life
- ~5X lower latency

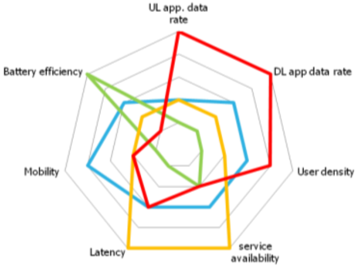


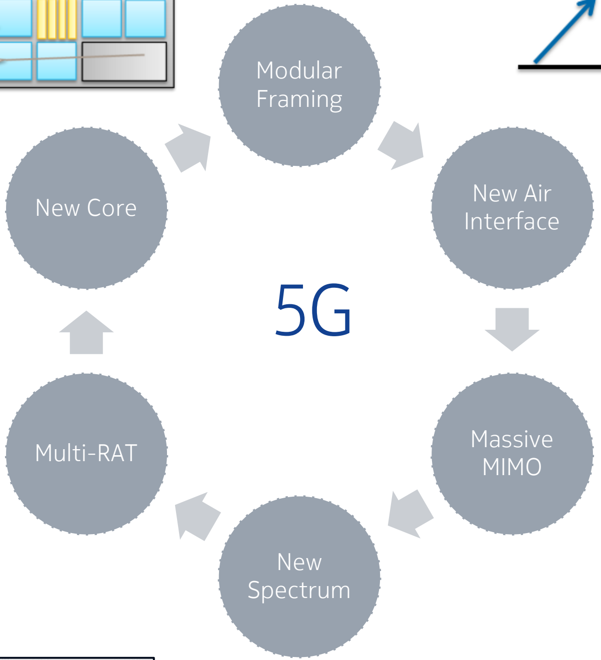



**New Virtualized + Software-Defined Core** for flexible routing through centralized, distributed, gateways optimized for any service mix



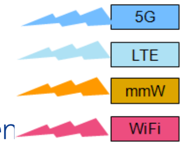



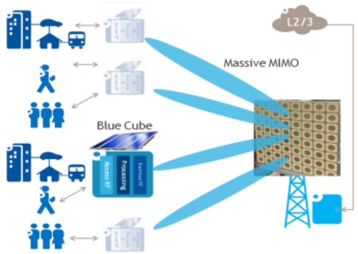

**Massive MIMO**
Higher spectral efficiency through spatial multiplexing (beamforming)

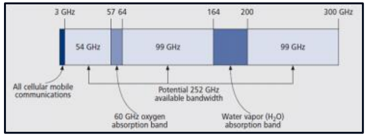
- ~5X increase in spectral efficiency

**Multi-RAT** with network controlled traffic steering and cell-less architecture

- ~2X increase data rate
- Guaranteed user/service experien



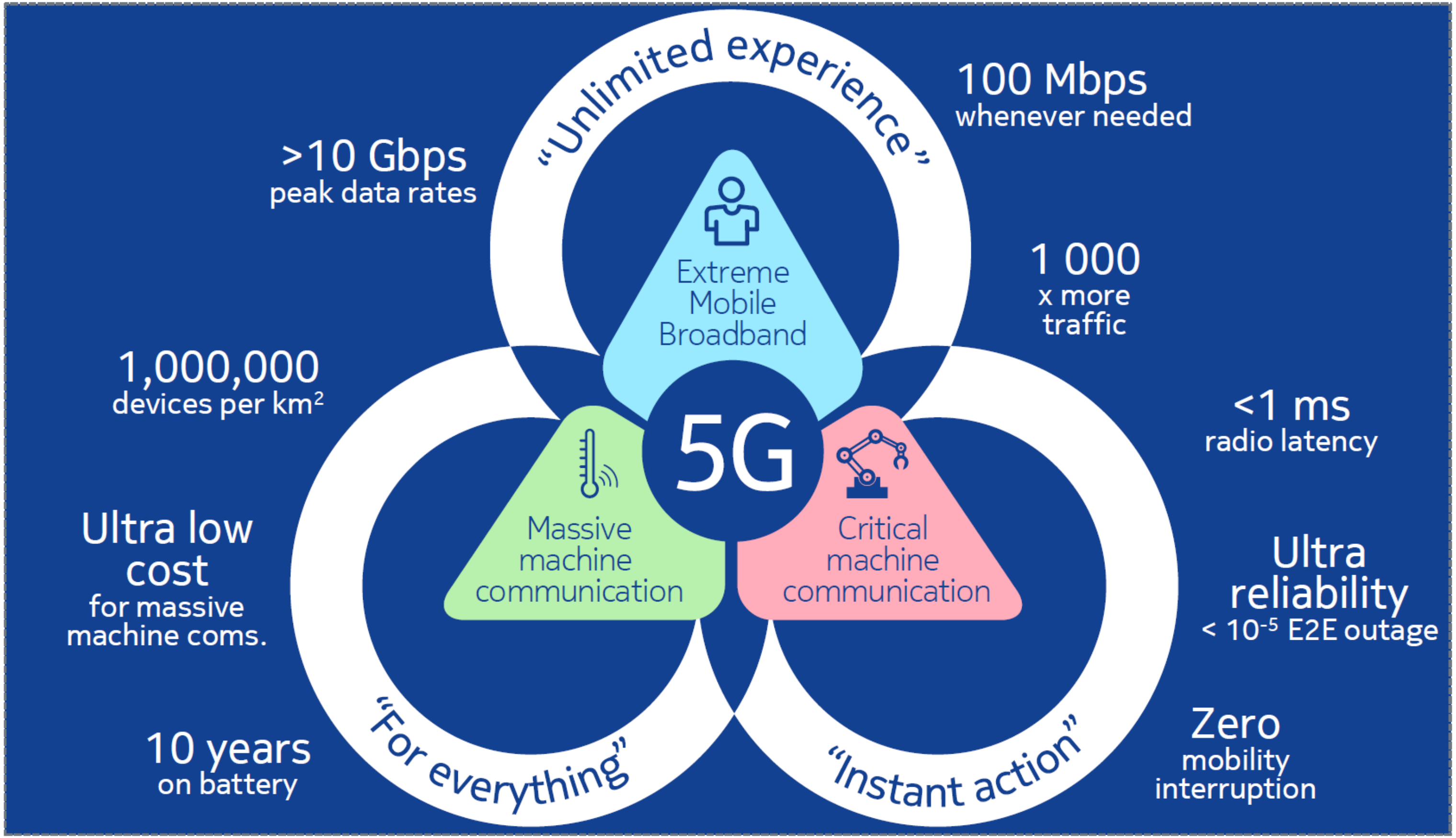

**New "mmWave" spectrum** small cells

- ~10X bandwidth

  <public>

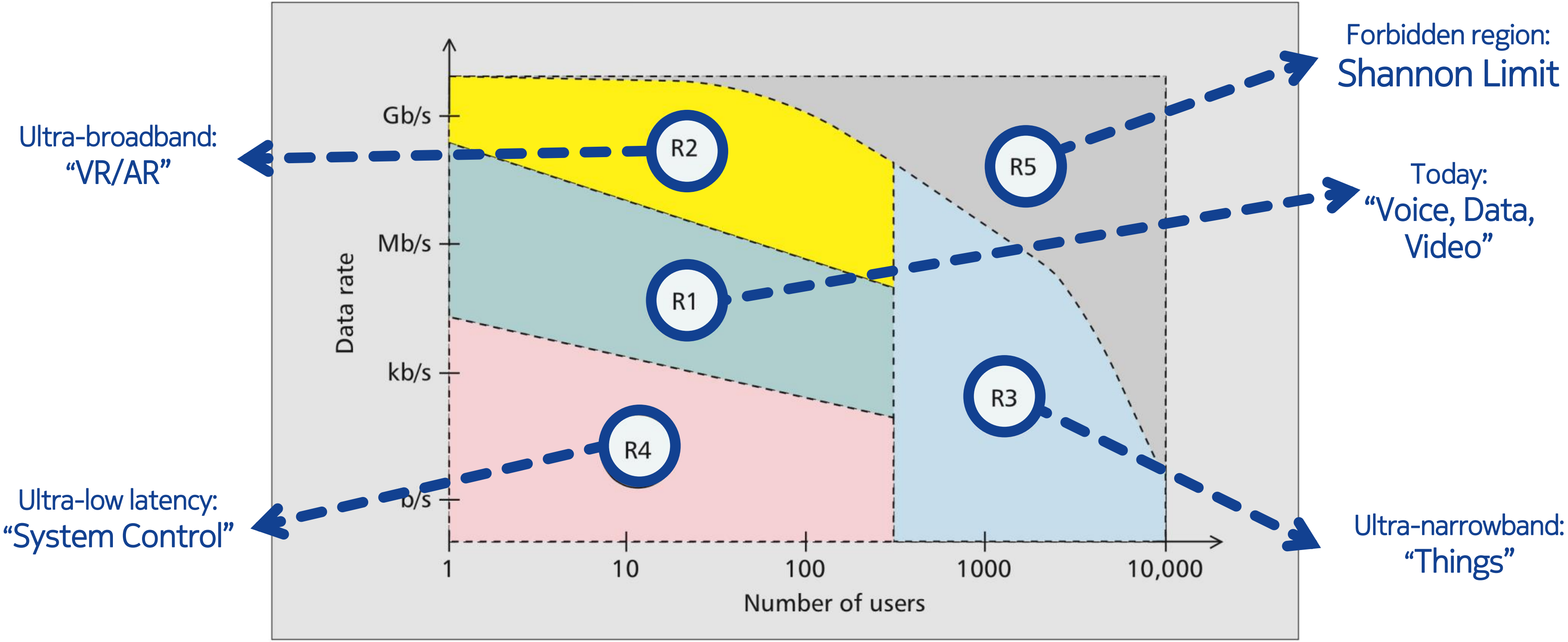
NOKIA Bell Labs

# 5G Target Requirements




   NOKIA Bell Labs

# The Simple Formula: 5G = R1+R2+R3+R4

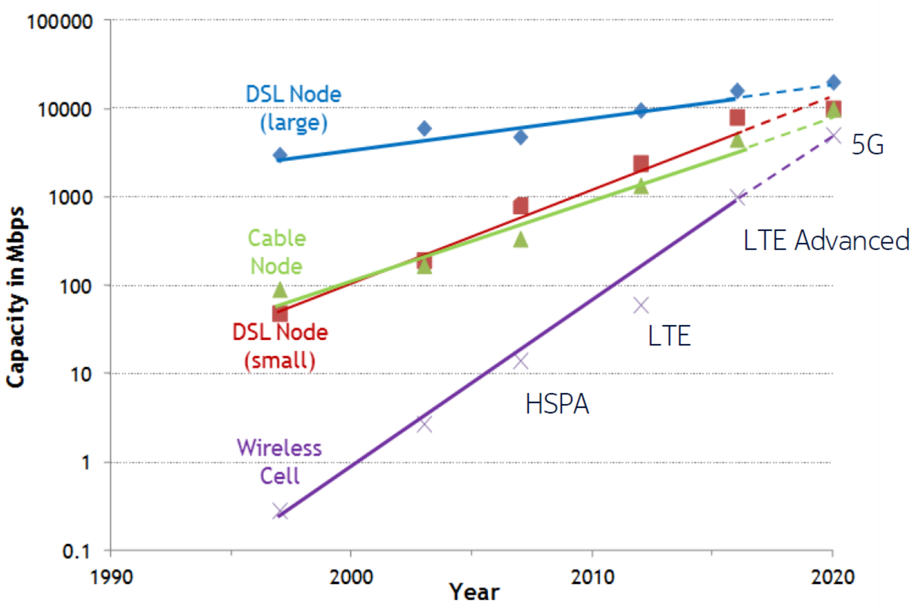



F. Boccardi, Bell Labs, IEEE Comms. Magazine, 201402

  <public> NOKIA Bell Labs

# Fixed Access

## Convergence at 10Gbps




- ~1 Gbps peak rates per household
- ~100 Mbps sustained data rates per household
- Self-installable CPE

Nokia Bell Labs

# 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)

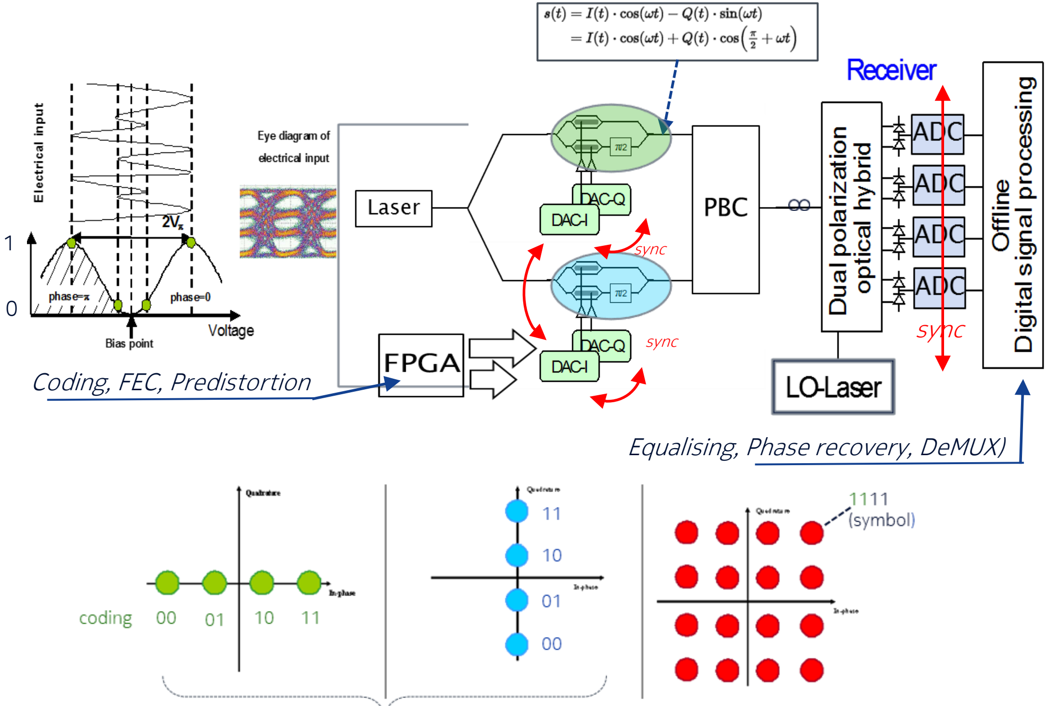
### *Inter* datacenter

- 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




16 possible I/Q combinations => mapped to
1 Symbol = 4 bits ($2^4$=16)

*Def. Symbol rate: 1Symbol/s = 1 Baud*

E.g. 16QAM Polarisation Multiplex:

- Adding *two* optical polarisations (in the PBC);

  *per polarisation*:

  - 4 bits coded into 1 symbol (i.e. 2 in In-Phase (I) and 2 in Quadrature (Q) component) => Modulator is driven by electrical four-level signal
  - After 90° phase rotation optical Q-signal is superposed with I-signal
- 4 bits transmitted per symbol interval
- Def. Symbol rate: 1 Symbol/s = 1baud
- 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

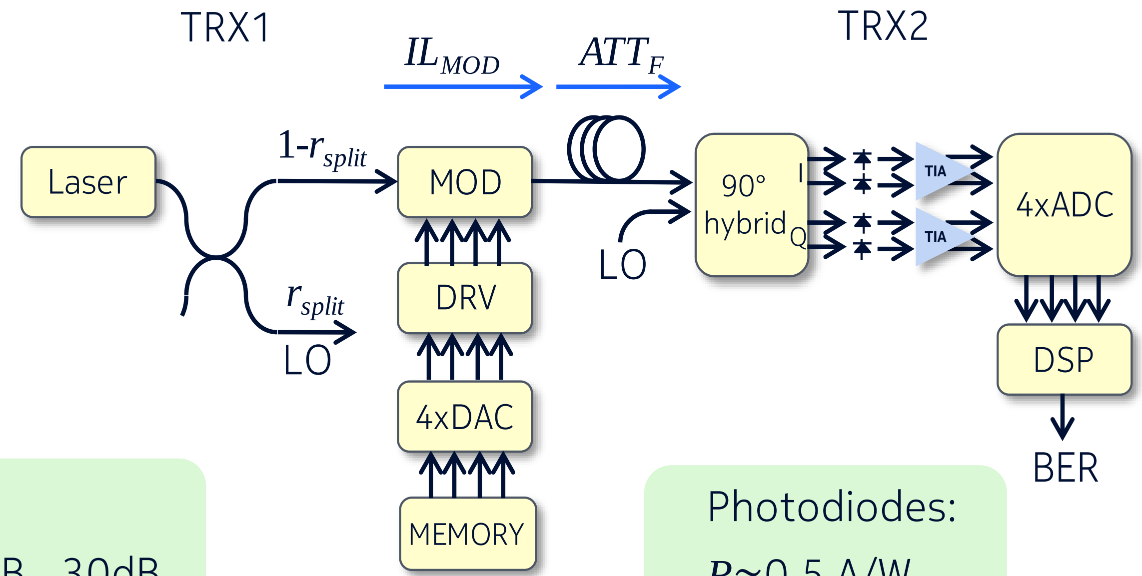
  

# Datacom optical transport

## 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 $\lambda$ (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 $\lambda$, the other options require multiplex

# System setup and power budget for low cost coherent Solution




LiNb:

$IL_{MOD} \approx 20\text{dB} \ldots 30\text{dB}$

Photodiodes:

$R \approx 0.5$ A/W

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

  <public>

GRAPHENE FLAGSHIP NOKIA Bell Labs

# 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

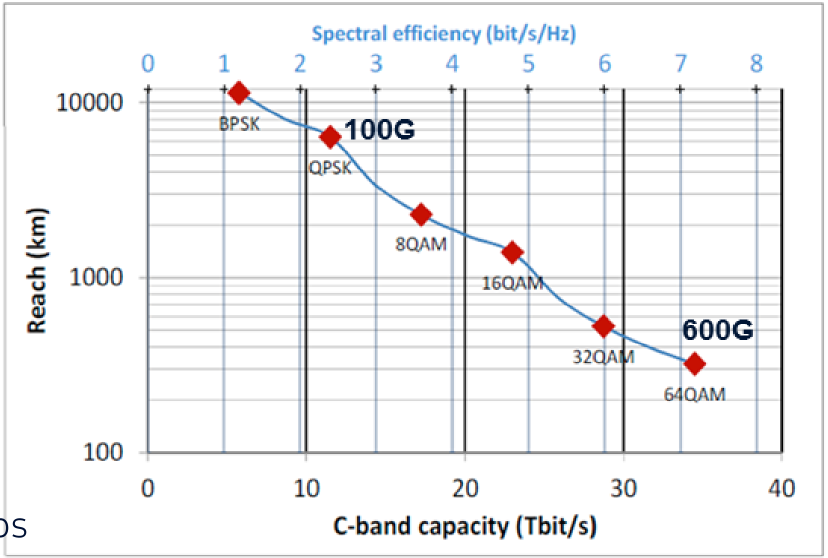
footprint reduction


**Graphene photonics may change the paradigm.**

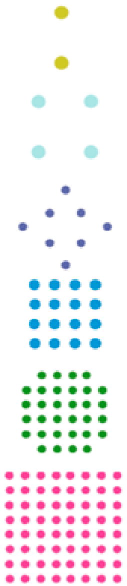
**It potentially allows to get rid of high performance power hungry analog ASICs.**

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

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




Baud rate 32.5Gbps



  <public> NOKIA Bell Labs

# … and here comes Graphene into the game

GRAPHENE FLAGSHIP

# Graphene – Material Properties / Component FOMs

- RT carrier mobility, ($e^-$ /$h^+$): 200000/200000
  - limited to 40000 $cm^2V^{-1}s^{-1}$ by optical phonon scattering on $SiO_2$ substrate; Si: 1400/450 ($e^-$/$h^+$) $cm^2V^{-1}s^{-1}$
  - Competitive modulation, detection and switching performance for mobilities >10000 $cm^2V^{-1}s^{-1}$, carrier conc. ~$10^{12}$ $cm^{-2}$
- *DC* Resistivity: 1 · 10-6 ; (Cu: 1.6·10-2) Ωcm
- Thermal conductivity: ~$5\cdot10^3$; (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 $\sigma_g = (\sigma_{g,r} + \sigma_{g,i}) = F(\omega, \Gamma, \mu_C, T, \ldots)$ -> Electronic control of conductivity
- Tunable Bandgap

## Comparison of Modulator Tech. Platforms

| Material | $V_\pi L$ (V mm) | Insertion loss (dB $mm^{-1}$) | $FOM_{PM}$ (V dB) |
|---|---|---|---|
| $LiNbO_3$ (E) | 50–100 | 0.4 | 20–40 |
| $LiNbO_3$ (E)[a] | 18 | 0.3 | 5.4 |
| InGaAsP/InP (E) | 5–10 | 0.7 | 3.5–7 |
| Si photonics (E) | 10–20 | 1–2 | 10–20 |
| Graphene (T) | 0.7–2.8 | 0.1–1.2 | 1–2 |

## MZI Modulator Performance:

| Modulator: operating wavelength (T/E) | $V_{bias}$ (V)/$V_{PP}$ (V) | ER (dB) @Gb $s^{-1}$ | L (mm) | Total IL (dB)/ PL (dB $mm^{-1}$) | $V_\pi L$ (V mm) | $FOM_{PM}$ (V dB) | Power (mW) | Energy (pJ $bit^{-1}$) @ Gb $s^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| Double SLG TWMZI: 1,550 nm (T) | 6.5/0.3 | 3.0[a] | 1.3 | 1.56[b]/1.2 | 1.6 | 1.92 | 0.45 | 0.01 @40 |
| Embedded (SiN) double SLG TWMZI: 1,550 nm (T) | 5/– | – | 0.17 | 0.02[b]/0.1[c] | 0.7 | – | – | – |
| Double SLG lumped: 1,550 nm (T) | 6.5/1 | 3[a] | 0.4 | 0.48[b]/1.2 | 1.6 | 1.92 | 12.8 | 0.32 @40 |
| TWMZI: 1,550 nm (E) | 0/0.36 | 3.5 @40 | 2 | 12.5[d]/2.25 | 7.5 | 16.87 | 1.3 | 0.032 @40 |
| Lateral p–n junction: 1,540 nm (E) | 5/6.5 | 6.5 @40 | 3.5 | 3.85[d]/1.1 | 29 | 31.9 | – | – |
| PAM4 TWMZI lateral p–n junction: 1,300 nm (E) | −0.5/2.16 | 6.0[e] | 2.8 | 5.0/1.02 | 14.7 | 15 | 135 | 4.8[e] |
| TWMZI lateral p–n junction: 1,300 nm (E) | 0/1.5 | 3.4 @40 | 3 | 5.5[d]/1.1 | 25 | 27.5 | 22.5 | 0.45 @50 |
| TWMZI lateral p–n junction: 1,300 nm (E) | 0/1.6 | 9.0 @16 | 3 | 5.4/1.2 | 16.7 | 20 | 165 | 10.3 @16 |
| TWMZI lateral p–n junction: 1,300 nm (E) | −0.5/1.85 | 4.4 @32 | 2.8 | 4.9/0.72 | 16.1 | 12 | 140 | 4.4 @32 |
| TWMZI lateral p–n junction: 1,550 nm (E) | −6/7 | 5.56 @50 | 7.35 | 6.91[b]/1.04 | 26.7 | 27.8 | 245 | 4.9 @56 |

*From Graphene-based integrated photonics for next-generation datacom and telecom.; M. Romagnoli et al., Nat. Rev. Mat., 3, 392-414 (2018*

# Integrated Photonics Technology

## Silicon photonics

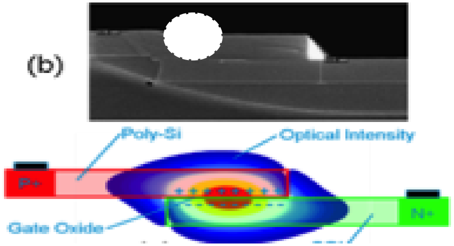
Technology
- Active photonic circuit
- **Implantation needed**
- **Ge epitaxy**

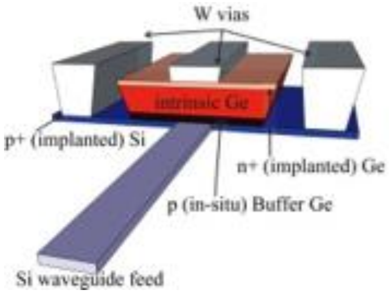
Approaches to functionalities
- Free carrier effect
- Thermo-optic effect

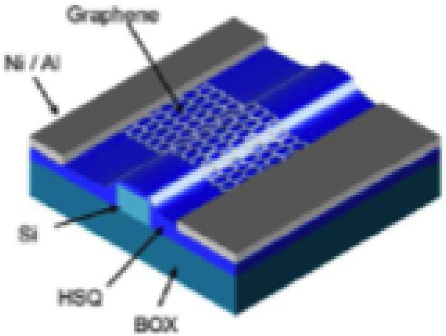
## Graphene photonics

Technology
- Passive photonic circuit
- **No implantation**
- **No epitaxy**

Approaches to functionalities
- Capacitive effect
- Thermo-optic effect



GRAPHENE FLAGSHIP NOKIA Bell Labs

# Photonic devices

## Silicon photonic devices

Modulators

- Electro-absorption (Franz Keldish)
  - SiGe alloys
  - **Wavelength selective**
- Phase
  - Free carrier
  - **FOM > 10dBV**

Switches

- Thermo-optic switch
  - Joule effect
  - **High static power consumption**

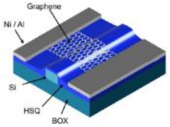
Detector

- Ge on Si
  - **High responsivity**
  - **High speed**

## Graphene photonic devices

Modulators

- Electro-absorption
  - Graphene capacitor
  - **Broadband**




- Phase
  - Graphene capacitor
  - **FOM < 10dBV (including loss)**

Switches

- Capacitive switch
  - Capacitive effect
  - **No static power consumption**

Detector

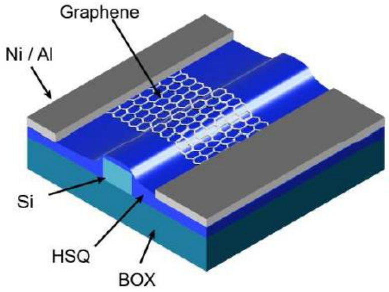
- Photoconductor, Schottky on Si, AC photodiode
  - **Low responsivity**
  - **High speed**

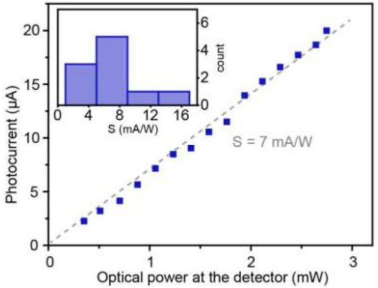
  

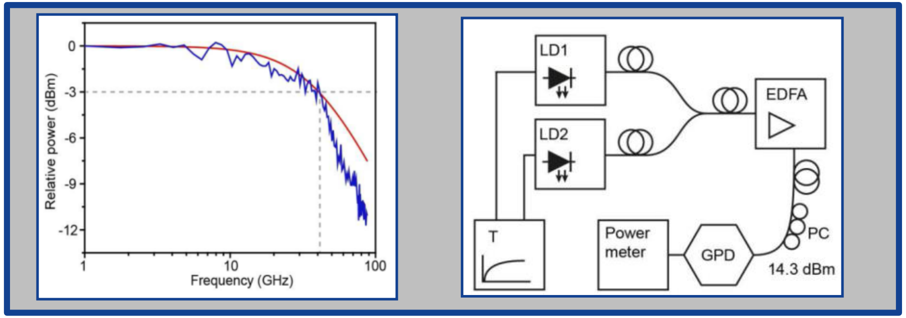
# FIRST STEPS:
## 50Gbps PHOTO DETECTOR ON Si-WAVEGUIDE (AMO GMBH, ALCATEL-LUCENT)

- 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);)*

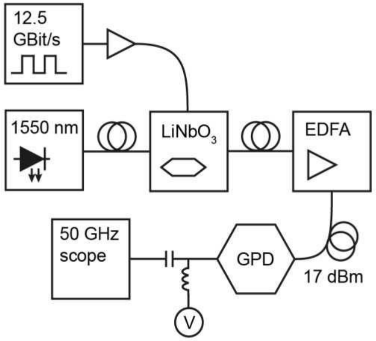
*Parts of this work have been performed in cooperation between AMO GmbH and Alcatel-Lucent Bell Labs within frame of European Flagship Graphene (604391)*

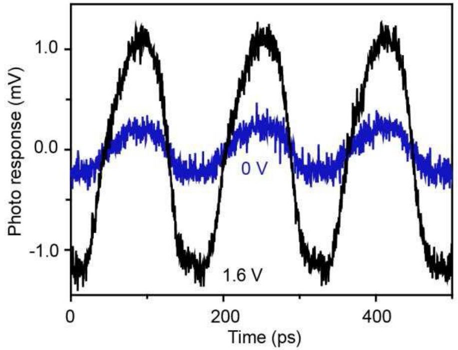
 

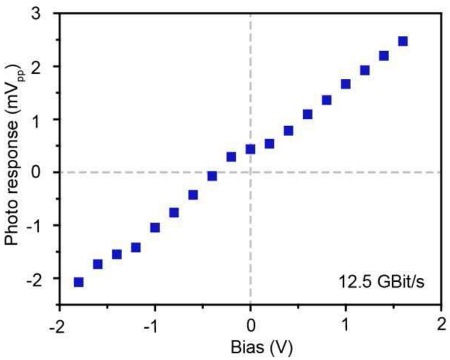
# 50Gbps Photo Detector on Si-Waveguide

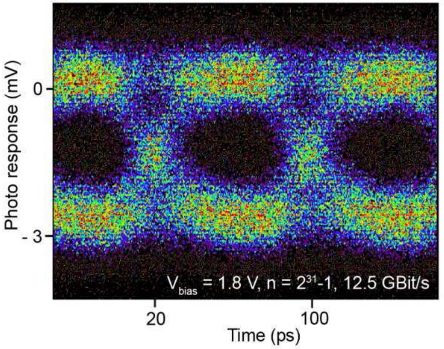
- Transmission Performance Measurement
  - GPD inserted into optical 12.5 Gbit/s link
  - Bit Sequence NRZ-OOK via LiNbO3 Modulator
  - λ=1550 nm, 17dbm (EDFA)

  - Photo response at GPD (still insufficient)
    - Zero bias: Vout=0.4 mVpp,
      but SNR is insufficient for data transmission
    - 1.6 V bias: Vout 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.



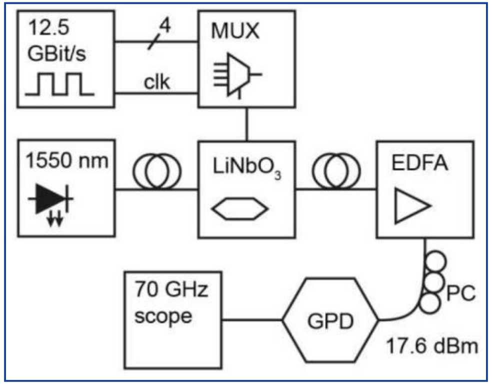

  <public>

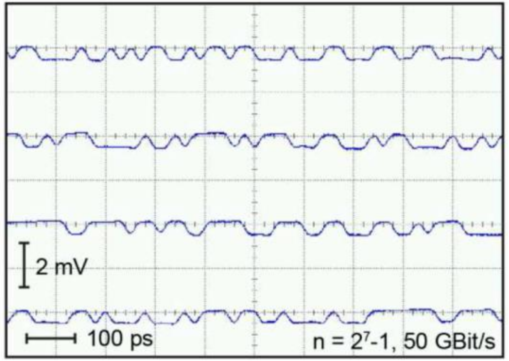
GRAPHENE FLAGSHIP NOKIA Bell Labs

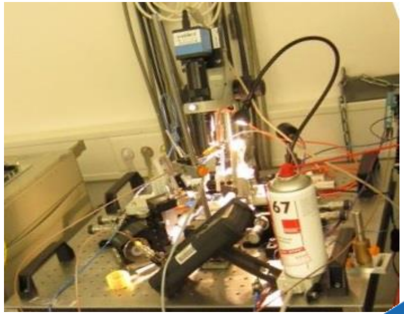
*Parts of this work have been performed in cooperation between AMO GmbH and Alcatel-Lucent Bell Labs within frame of European Flagship Graphene (604391)*

# 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 $LiNbO_3$ modulator
  - λ=1550 nm, 17.6dbm (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
    - $T_{rise,\ (10\%\ to\ 90\%)}$ = 9 ps, i.e. BW = 39 GHz







GRAPHENE FLAGSHIP

NOKIA Bell Labs

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)

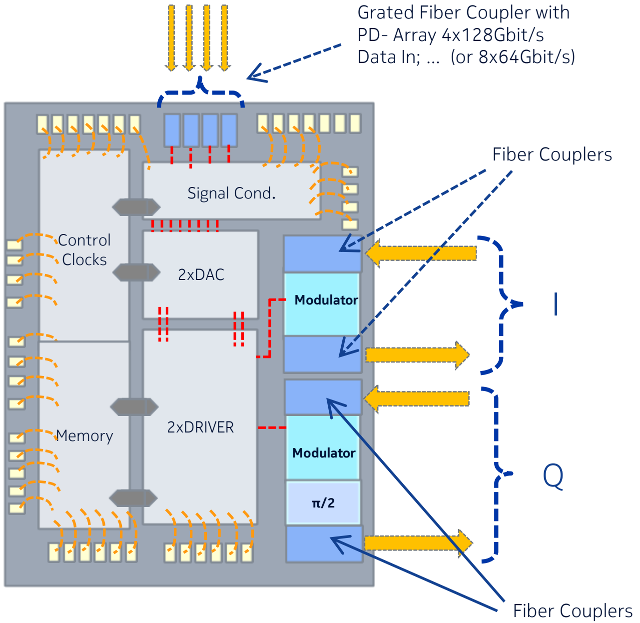
# Vision: Integrated high Performance Optical TRX PIC

## 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 !!**

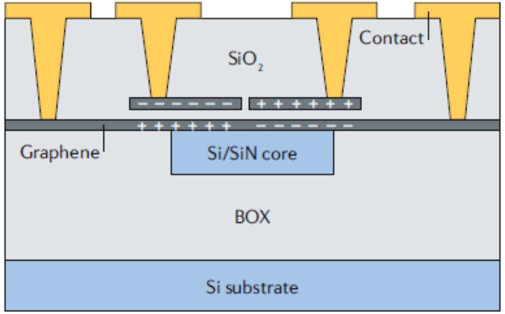



  <public> NOKIA Bell Labs

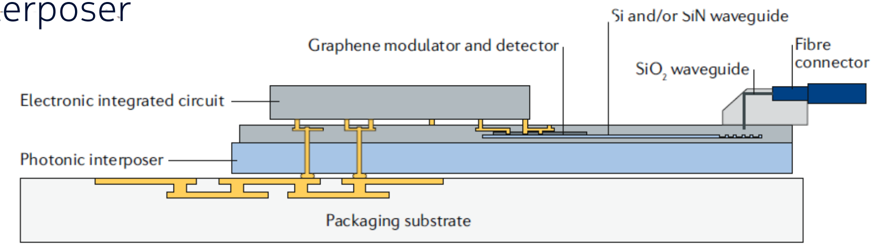
# Coming true …

## Exemplarily Architectures

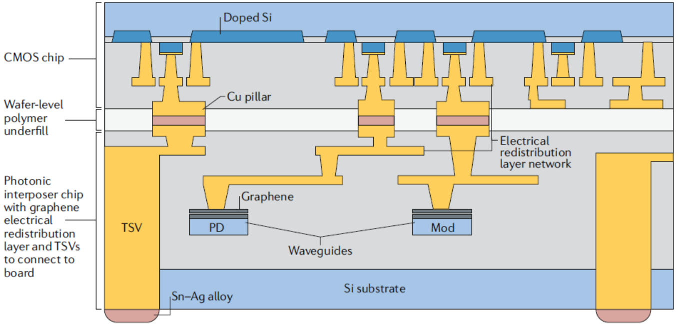
### Double- gated thermoelectric photodetector




### Graphene-based transceiver integrated in a Si photonic interposer




### CMOS circuit on a SLG photonics circuit

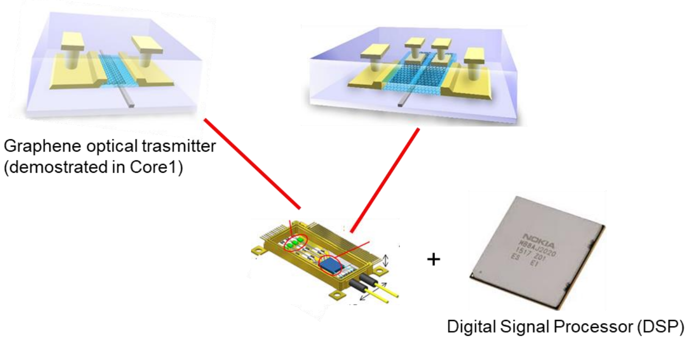



*Graphene-based integrated photonics for next-generation datacom and telecom.*
*M. Romagnoli et al., Nat. Rev. Mat., 3, 392-414 (2018*

   GRAPHENE FLAGSHIP NOKIA Bell Labs

# 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

NOKIA