THE MOBILE PHONE
HIGH-TECH IN YOUR POCKET

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CONTENTS

- Update on State of Mobile Communications Industry
- Evolution: From GSM to LTE-Advanced
- Inside Look: High-End Smartphone
- Up Next: 5G
- Conclusion
GLOBAL MOBILE SUBSCRIPTIONS: BY GEO

Total: 7.3 billion

- Inactive subscriptions included
- Multiple devices (phone, tablet, e-reader, car, M2M)
- Multiple SIM ownership

Source: Ericsson Mobility Report, Nov. 2015
Handset market growth slows down, becomes replacement-driven.

Phase-out of devices supporting only legacy standards, LTE gains share.

5G initial commercial deployment in 2020.

Source: Ericsson Mobility Report, Nov. 2015
GLOBAL MOBILE SUBSCRIPTIONS: IOT

Source: Ericsson Mobility Report, Nov. 2015
GLOBAL MOBILE SUBSCRIPTIONS: DATA

Global mobile traffic (monthly ExaBytes)

- Orange: Data: mobile PCs, tablets, and mobile routers
- Red: Data: smartphones
- Yellow: Voice

Source: Ericsson Mobility Report, Nov. 2015
GLOBAL MOBILE SUBSCRIPTIONS: DATA

- Exponential mobile data growth
  → Quest for more bandwidth
- More frequency bands
- High-order modulation
  (256QAM DL, 64QAM UL)
- MIMO (2x2, 4x4)
- Link aggregation
  (2CA→3CA→4CA, LAA/LWA)
- 5G (2020+)

Source: Ericsson Mobility Report, Nov. 2015
3GPP EVOLUTION – DOUBLING DATA RATE EVERY 18 MONTH

Bits per Second

1G

1M

1k

1


GSM, 10 kb/s

200 kHz

1 bit/symbol (GMSK)

1 (of 8) time slots

GPRS

UMTS, 384 kb/s

5 MHz

2 bits/symbol (QPSK)

1/8 code space

UMTS

HSPA, 42 Mb/s

5 MHz

6 bits/symbol (64-QAM)

15/16 code space

2 spatial MIMO streams

HSPA

HSPA+, 42 Mb/s

5 MHz

6 bits/symbol (64-QAM)

15/16 code space

8 spatial MIMO streams

HSPA+

LTE-A, > 1Gb/s

100 MHz

6 bits/symbol (64-QAM)

15/16 code space

8 spatial MIMO streams

LTE-A

LTE

GSM, 10 kb/s

200 kHz

1 bit/symbol (GMSK)

1 (of 8) time slots

Source: Intel, IUS 2015

CMOS Technology Nodes

- 1995: 0.35µm → GSM
- 2001: 130nm → UMTS
- 2006: 65nm → HSPA
- 2010: 32nm → LTE
- 2015: 14nm → LTE-A Pro
Spatial diversity (multipath) is exploited

- Channel matrix $H$ must be invertible

- In mobile application:
  - 2x2 MIMO in HSPA+ possible, but not realized (low-cost 2G/3G handsets w/o diversity antenna/receive path)
  - 2x2 MIMO in LTE mandated by standard

THE MIMO CHALLENGE (2X2 → 4X4)

- Required antenna separation for MIMO

- Notebook form factor
- Tablet form factor
- Phone form factor

Source: B. Adler, EuMW 2013
2016/2017 LTE BAND DEPLOYMENT FORECAST

Source: Intel, IUS 2015

NOTE: Not all bands are available in a single region

1 Assuming full 5.8GHz as one band

ULB
- 2 Bands
- Ø 25MHz

LB
- 13 Bands
- Ø 39MHz

MB
- 13 Bands
- Ø 51MHz

HB
- 6 Bands
- Ø 85MHz

UHB
- 3 Bands
- Ø 333MHz
EXAMPLE: HIGH-END SMARTPHONE (2015-ERA)

Supported radio-access technology and bands

- **GSM/EDGE**
  - 850MHz, 900MHz, 1800MHz, 1900MHz

- **CDMA EV-DO Rev. A**
  - 800 MHz, 1700/2100MHz, 1900MHz, 2100MHz

- **UMTS/HSPA+/DC-HSDPA**
  - 850MHz, 900MHz, 1700/2100MHz, 1900MHz, 2100MHz

- **TD-SCDMA**
  - 1900 (F), 2000 (A)

- **LTE FDD**
  - Bands 1, 2, 3, 4, 5, 7, 8, 12, 13, 17, 18, 19, 20, 25, 26, 27, 28, 29, 30

- **TD-LTE**
  - Bands 38, 39, 40, 41

Source: Phone manufacturer’s homepage
EXAMPLE: HIGH-END SMARTPHONE (2015-ERA)

Supported radio-access technology and (implemented) bands

- **GSM/EDGE**
  - 850MHz = B5, 900MHz = B8, 1800MHz = B3, 1900MHz = B2

- **CDMA EV-DO Rev. A**
  - 800MHz = B26, 1700/2100MHz = B4, 1900MHz = B2, 2100MHz = B1

- **UMTS/HSPA+/DC-HSDPA**
  - 850MHz = B5, 900MHz = B8, 1700/2100MHz = B4, 1900MHz = B2, 2100MHz = B1

- **TD-SCDMA**
  - 1900 (F) = B39, 2000 (A) = B34

- **LTE FDD**
  - Bands 1, 2, 3, 4, 5, 7, 8, 12(17), 13, 17, 18, 19, 20, 25(2), 26(5,18,19), 27, 28(A/B), 29, 30

- **TD-LTE**
  - Bands 38, 39, 40, 41(38)

Source: Phone manufacturer’s homepage; niviuk.free.fr (frequency bands)
LTE CARRIER-AGGREGATION

Source: Qualcomm, “Delivering on the LTE Advanced promise”, 2016
LTE CARRIER-AGGREGATION TYPES

**Inter-band 2-CA**

- Frequency Band A
  - Channel 1
  - LO1
- Frequency Band B
  - Channel 2
  - LO2

**Intra-band contiguous 2-CA**

- Frequency Band A
  - Channel 1
  - LO1
  - Channel 2
  - LO2

**Intra-band non-contiguous 2-CA**

- Frequency Band A
  - Channel 1
  - LO1
  - Channel 2
  - LO2

Note: NC intra-band can cause very small duplex distance between TX and SCC

Source: Intel, IUS 2015
**COMPLICATIONS DUE TO CARRIER AGGREGATION**

**TX Harmonics**
- PA H2/H3 → RX2
- TX in LB (e.g. band 12, 710MHz) harmonics fall into HB (e.g. band 4, 2130MHz)
- Very stringent linearity requirements for signal chain PA up to antenna (switches, filters, coupler)

**LO-LO Interference**
- Harmonic of LO for RX1 is received by harmonic of LO for RX2 (e.g. 2*LO for band 8, 930MHz = LO for band 3, 1860MHz)
- Very stringent requirements for IC design to isolate blocks and reduce interference

**MB-MB Combinations**
- Some CA band combinations require 4 diplexing filters (e.g. band 1 and band 3 or band 2 and band 4)

Source: Intel, IUS 2015; M. Kahrizi, ISSCC 2016 Forum
### LTE: THE NEED FOR SPEED

- **LTE 2x2 MIMO, 20MHz BW, 64QAM** → 150Mbps (category 4)
- **LTE-Advanced 2x2 MIMO, 2x20MHz BW, 64QAM** → 300Mbps (category 6)
- **LTE-Advanced 2x2 MIMO, 3x20MHz BW, 256QAM** → 600Mbps (category 12)
- **LTE-Advanced 2x2 MIMO, 4x20MHz BW, 256QAM** → 800Mbps (category 15)
- **LTE-Advanced 2x2 MIMO, 5x20MHz BW, 256QAM** → 1000Mbps (category 16)

  ◯ Alternative implementation as 4x4 MIMO, 2x20MHz + 2x2 MIMO, 1x20MHz, 256QAM

*Source: 3GPP*
EXAMPLE: HIGH-END SMARTPHONE

Source: Chipworks Teardown Report, BPT-1509-801
DIGITAL & MEMORY

Cellular modem

Application processor + stacked DRAM

Flash memory (NV)

Wi-Fi + BT modem

Source: TECHINSIGHTS, teardown.com
ANALOG, MIXED-SIGNAL & RF

Cellular RF (PA, filter)  Power management  Sensors (proximity, ambient light, compass, gyro, accelerometer, barometer, fingerprint)

Audio

Cellular RF (transceiver, filter)  Power management  Power management  Audio  NFC

Interface (microphones, touch, display, camera)

Wi-Fi + BT (transceiver)

Source: TECHINSIGHTS, teardown.com
CO-EXISTENCE IS CRITICALLY IMPORTANT

Source: Intel, Erlangen DocShop 2011
RF FRONT-END DIAGRAM (SIMPLIFIED)
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NEXT GENERATION WIRELESS (5G)

- Hot topic in academia & industry
- Latency <1ms (LTE ~10ms)
- 10Gbps peak, 100Mbps minimum
- Billions of devices, 10yrs on battery
- Using frequencies between 3.4GHz and 5GHz, 1.4-1.5GHz, 0.5-0.7GHz
- New technology: mm-Wave (28/38GHz)
  - Low-power implementation is key

Source: Anritsu, “Understanding 5G”
POSSIBLE FREQUENCY BANDS FOR MM-WAVE ACCESS

United States

European Union

Korea

Japan

Source: B. Adler, EuMW 2013
POSSIBLE FREQUENCY BANDS FOR MM-WAVE ACCESS

Source: B. Adler, EuMW 2013; J. Wells, IEEE Microwave Magazine, 2009
THE MM WAVE CHALLENGE

HPBW: 70-90°

Source: B. Adler, EuMW 2013; A. Niknejad et al., CICC 2015
THE MM WAVE CHALLENGE

HPBW: 2-3°

Source: B. Adler, EuMW 2013; A. Niknejad et al., CICC 2015
THE MM WAVE CHALLENGE

- Path loss at mm-Wave is considerable higher than at 5 GHz, but antenna gain is higher for same aperture
- To compensate for this loss, beamforming (BF) is needed
- BF allows focusing the energy towards the intended receiver
  - Advantage: Increased security, no multi-path, increased capacity
  - Disadvantage: Beam steering, lots of mm-Wave signal paths
- Beamforming is practical at mm-Wave due to the small signal wavelength using phased arrays
  - Base station: Massive MIMO (>100 antennas)
  - Mobile station: 4..32 antennas

Source: B. Adler, EuMW 2013; A. Niknejad et al., CICC 2015
EXAMPLE IMPLEMENTATION

Source: G. Mangraviti et al., ISSCC 2016
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KEY TAKEAWAYS

- The mobile phone has been (and still is) a major driver of innovation
  - Radio technology
  - Sensors & user interfaces
  - Processing power (CPU, GPU) & storage (FLASH)
  - Power management

- The progress from GSM (kbps) to LTE-Advanced (Gbps) in around 20 years has been enabled by
  - Improving technologies (CMOS scaling according Moore’s law)
  - Huge investment in R&D