Chapter 7: Mobile

The 2021 edition of this Chapter will be posted early in 2022; please check back (eps.ieee.org/hir) to replace this earlier version with the latest one.

The HIR is devised and intended for technology assessment only and is without regard to any commercial considerations pertaining to individual products or equipment.

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Chapter 7: Mobile

This chapter is in preparation, and will be integrated into the Roadmap at Version 1.1, planned for the end of 2019. In its place is the following summary and a series of slides giving the current status of mobile electronics and some information that is relevant to the progress needed over the next 10 to 15 years.

Executive Summary

Mobile is a major driver for electronics innovation, representing a large proportion of electronics market revenue, the largest consumption of advanced nodes semiconductors, and – perhaps most important of all – is the technology directly used by 75%-80% of the global population...

The mobile chapter is one of the six market application chapters in the Heterogeneous Integration Roadmap (HIR). The mission of the Mobile Technical Working Group (TWG) is to articulate the market and technology landscape, identify challenges and roadblocks for heterogeneous integration technologies, and their potential solutions for future generation of heterogeneous integration requirement in mobile device and mobile infrastructure. In this 1st edition of the HIR Mobile Chapter we shall put major emphasis on articulating the driving forces and leading-edge packaging technology as the base foundation from which to project the future directions with near- and long-term horizons. The working plan is:

- Overview the market landscape, driving forces and future directions
- Review the heterogeneous integration focus in mobile
- Articulate crucial enabling heterogeneous integration technologies
- Describe linkage to other HIR Chapters to bring out the full picture
- Project future directions, challenges and potential solutions – near and long term
- Plan for the next edition
Heterogeneous Integration Roadmap

MOBILE

Technical Working Group
William Chen, Chair
Benson Chan, Mark Gerber, Brandon Prior

Outline

- Executive Summary
  - Mobile Technical Working Group Mission and Plan
- The Big Picture
  - Mobile Economy and Global Mobile Network
  - Data Growth and 5G
- Heterogeneous Integration inside the Smart Phone
  - Die Stacking & Package-on-Package (PoP)
  - Inside the Premier Smart Phones
- 5G – Area for Innovation and Creativity
  - 5G in the Smart Phone
  - Antenna-in-Package (AiP)
- Heterogeneous Integration for the Mobile Network
- Future Visions
- Wrap-up
  - Difficult Challenges
  - Summary
- References and Acknowledgments
The Big Picture

Mobile Contribution: $1.14 Trillion to 2018 Global GDP

GSMA (www.gsma.com) is an industry association representing the worldwide mobile communication industry. In GSMA report “The Mobile Economy 2019” the mobile industry contributed $1.14 trillion to 2018 Global GDP, as shown above.
Adding Productivity Impact of $2.27 trillion and $0.5 trillion the total became $3.92 trillion equal to 4.6% 2018 Global GDP source: gsma.com

Global Mobile Subscribers as percentage of population
Source: Ericsson Mobility Report Q2 2019
Mobile Subscription By Technology (billions)
Source: Ericsson Mobility Report Q2 2019

Mobile Data Growth
Source: Ericsson Mobility Report 2019

Global mobile data traffic and year-on-year growth (GB per month)
Gartner (08-22-2019) projected that communication service providers (CSPs) using non-stand alone (NSA) technology to introduce 5G service initially. New Radio 5G (NR) equipment will start to roll out in 2020.

CSP Wireless Infrastructure Revenue Forecast (source: Gartner 08-22-2019)

<table>
<thead>
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<th>Segment</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
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<td>5G</td>
<td>612.9</td>
<td>2,211.4</td>
<td>4,176.0</td>
<td>6,805.6</td>
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<tr>
<td>2G</td>
<td>1,503.1</td>
<td>697.5</td>
<td>406.5</td>
<td>285.2</td>
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<td>3G</td>
<td>5,578.4</td>
<td>3,694.0</td>
<td>2,464.3</td>
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<td>LTE and 4G</td>
<td>20,454.7</td>
<td>19,322.4</td>
<td>18,278.2</td>
<td>16,352.7</td>
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<td>Small Cells</td>
<td>4,785.6</td>
<td>5,378.4</td>
<td>5,858.1</td>
<td>6,473.1</td>
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<tr>
<td>Mobile Core</td>
<td>4,599.0</td>
<td>4,621.0</td>
<td>4,787.3</td>
<td>5,099.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37,533.6</strong></td>
<td><strong>35,924.7</strong></td>
<td><strong>35,970.5</strong></td>
<td><strong>36,484.1</strong></td>
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Global Smart Phone Adoption
Source: GSMA The Mobile Economy 2019

Global smartphone adoption will reach 80% by 2025
Smartphone connections as a percentage of total mobile connections
“In 2017, global smartphone sales reached close to 1.5 billion units—one for every fifth person on earth (Figure 1.1.1). Demand has been driven by the increasing use of smartphones as the main computing platform across the world, substituting in part for personal computers. Mobile technology and services are estimated to have contributed $3.6 trillion (4.5%) to 2017 global GDP (GSMA 2018).”

“Smartphones contributed about one-sixth the estimated growth rate of global trade in 2017. This growth was driven mainly by an increase in value added per unit, rather than units sold, which declined for the first time on record.”

Source: IMF World Economy Outlook, April 2018, page 34.
Inside the Mobile Phone

Mobile 1926

The idea for people to communicate freely anywhere untethered has existed long ago. Shown to the right is a cartoon “wireless telephony” from artist Karl Arnold published in the German magazine Simplicissimus in 1926.

Source: Wikipedia – History of Mobile Phone
Smart Phone

- The smartphone is the major human-machine interface device, with its 5bn units installed base.
- More functions and intelligence added to interact with human, machine and environment around the world.
- It is the platform for most advanced nodes and innovations to meet the consumers “unfulfilled” needs.

From L to R: Apple iPhone XS Max, Samsung Galaxy S9+, Huawei 20 Pro

Smart Devices (Phone) (1)

The Smartphone is the “one device” for human to human and human to machine interfacing. It is a “society-transforming technology” that implemented a confluence of functions in addition to telephony – internet and web access including web browsing, search, GPS map, touch screen, large display, adequate battery life, and expanding Apps.

By adding new functions (such as face recognition) on a regular basis from generation to generation, the manufacturers build in the upgrade cycle for consumer buyers. In addition to electronics there are mechanical, thermal and operating design requirements including the toughened glass required for touch screens and lithium ion battery for sufficient battery life.
Smart Devices (Phone) (2)

Smartphones today can have from 10 to 24 devices packaged as SiP. SiP counts above 20 may be found in flagship smartphones, with 24 being found in the early iterations of 5G phones. The SiPs include:

- 2 and 5 Camera Modules
- 1-2 Optical Sensors (from simple proximity to full facial recognition)
- At least 3 MEMs Sensors (accelerator, gyro, pressure)
- 1-2 stacked Memory Packages with controller
- 1-4 Power Amplifier Modules
- 1-3 switch filter modules
- WLAN/Bluetooth Module
- Power Management
- PoP – Application Processor & baseband processor
- Antenna Module - Antenna-In-Package (AiP) for 5G phones

As the phone continue to add more functions to meet market demands, the use of SiPs continue to increase.

Heterogeneous Integration through SiP

- In Gordon E. Moore’s famous Moore’s Law paper he said “It may prove to be more economical to build large systems out of smaller functions, which are separately packaged and interconnected. The availability of large functions, combined with functional design and construction, should allow the manufacturer of large systems to design and construct a considerable variety of equipment both rapidly and economically.”


- We may paraphrase his words as follows: “It may prove to be more economical to build large systems out of smaller functions through Heterogeneous Integration into SiPs & Modules, which are separately packaged and interconnected. The availability of large functions, combined with functional design and construction, should allow the manufacturer of large systems to design and construct a considerable variety of equipment both rapidly and economically.”
SiP Tool Box - Enabling Technologies for Mobile

SiP Enabling Technologies for Mobile

1. Interconnection
   - Wire Bond
   - Flip Chip
   - Substrate

2. Encapsulation
   - Exposed Die/Component
   - Irregular Shape
   - Selective Area
   - Double Sided Molding

3. Fanout & Wafer Bumping
   - UF/Cu Pillar
   - WLCSP
   - FOWLP/FOCOS

4. Passives/IPD
   - 0201/01005
   - 008004
   - Glass IPD

5. Embedded
   - Passive
   - Active (a-EASI)
   - Active (a-ESUB-TDK)

6. MCM
   - Die Stacking
   - 2.5D, 3D/TSV
   - Package Stacking - PoP, PiP
   - Side by Side

7. System Assembly
   - HD-SMT
   - ACF Bonding
   - Laser Welding
   - Flex Bending

8. MEMS / Sensor/integration
   - Motion
   - Environmental
   - Optical

9. Shielding
   - Conformal
   - Compartmental
   - Selective

10. Antenna
    - A-Sh/Ap
    - Package integration

11. MEMS / Sensor/integration
    - HD-SMT
    - ACF Bonding
    - Laser Welding
    - Flex Bending

SiP/SiM Modules Heterogeneous Integration in Smart Phone

Integration / Miniaturization
Optimization / Simplification

Power Management
- DC/DC
- PMIC
- MEMS

Wireless
- Combo WiFi, BT, GPS, FM
- Broadband WiMAX

CPU/MCU
- High BW PoP
- 2.5D/3D TSV

RF/FEM
- PAM
- FEM
- Tx/Rx

Storage
- Camera Module
- Biometric Sensor
- Component Flash
- SSD
Galaxy S9+ Block Diagram (approximate)

Source: TechSearch

Copyright © 2018 TechSearch International, Inc., adapted from TPSS.

Looking inside the 3 Premier Phones

Apple iPhone XS Max
Samsung Galaxy S9
Huawei Mate 20 Pro

Main Board
Secondary Board(s)
Battery
Speaker
Main Camera
Biometric Sensor
Main Boards Layout of three Premier Phones

Main Boards Layout
Source: Prismark

SiP/SiM Module in iPhone 8 Main Board Assembly

Device Advanced Node – 10 nm

10 nm Processor/DRAM

FAN OUT SiP 1
SiP 8
WLP (WLCSP) 11

Memory Stacked Die 2

Teardowns of Apple XS Max, Samsung Galaxy S9+ and Huawei 20 Pro all show similar adoption of leading edge Heterogeneous Integration

Photo source: Prismark/Binghamton University
Packaging for the Application Processor (AP)

Stacked Die Packaging for Application Processor
and Baseband Processor

For application processors, there are three major stacked SiP in volume production:
  • Stacked-Die-in-Package
  • Package-on-Package (PoP) based upon Flip Chip CSP
  • PoP based upon FO-WLP Fan-Out Wafer Level Package (FO-WLP) or Panel Level Fan-Out (PLP)

The first two utilize mature assembly and materials/tools and are widely practiced; Apple has been the single user of the wafer fan-out approach for application processors. Recently, Samsung has released a smart watch processor using a form of PanelLevel Fanout Package.

Stacked-Die is widely used for memory packaging, accounting for 90% of the stacked die products. See “Advances in Memory Die Stacking” ECTC 2018, by Andreas Marte et al
Stacked-Die-in-Package

Shown below is an example of stacked die in package with a processor die packaged in FCCSP format as the bottom package. FCCSP offers a lower profile, better electrical performance, and higher I/O than a conventional wire bond CSP package. The Intel baseband processor found in the iPhone XS is packaged in a 8x9mm FCCSP with a three-layer embedded trace-substrate [ETS]. Source: Prismark & Binghamton University

Package-on-Package (PoP) (1)

Package-on-Package (PoP) is described in Wikipedia as “an integrated circuit packaging method to combine vertically discrete logic and memory ball grid array (BGA) packages. Two or more packages are installed atop each other, i.e. stacked, with a standard interface to route signals between them. This allows higher component density in devices, such as mobile phones, personal digital assistant (PDA), and digital cameras.” Source: Wikipedia

PoP solutions are commonly used in baseband and applications processors in mobile phones. High-end phones have seen the fastest adoption of PoP packaging to provide high I/O and performance requirements. The main advantage of stacked PoP is that devices can be separately fully tested before assembly.

PoP are used in many high-end phones. This market is expected to continue at around 800M units per year. Apple, Qualcomm, Samsung, Huawei, and MediaTek remain the largest users of PoP, and many others are in volume production.
Package-on-Package (PoP) (2)

The three schematic figures below are three different types of PoP Packages in production today in smart phones, tablets and smart watches.

To the left is the Flip Chip CSP PoP with the Logic Die (Application Processor or Baseband) assembled on a substrate in the form of FCCSP. The middle figure with an additional substrate to accommodate additional I/O from HBW memory packages represents the MCeP PoP. To the right is the Fan Out PoP used by TSMC InFO wafer level technology for the Apple Smart Phone and Smart Watches and by Samsung Panel Level technology for Samsung Smart Watches.

Source: The 3 figures below are taken from Yole Development Report “Fanout Packaging 2019 Technology & Market Trends”

Examples of three types of PoP

Source Yole Report

- Example of Flip-chip package for APE – Exynos 8 APE in Samsung Galaxy S7
  Source: System Plus Consulting APE comparison report

- Example of MCeP package for APE – Qualcomm’s Snapdragon 820 APE in Samsung Galaxy S7
  Source: System Plus Consulting APE comparison report

- Example of Fan-Out package for APE – Apple’s A11 APE in iPhone 8
  Source: System Plus Consulting APE comparison report
PoP Summary

- PoP is the dominant solution for mobile processors and memory packaging, trading off space constraint and cost and performance.
- Apple AP has chosen the Fanout technology for its AP and memory packaging.
- Samsung has chosen Panel level Fanout for its smart watch.
- In the examples for Samsung Galaxy S7, the Exynos 8 AP and the Qualcomm Snapdragon 820 AP selected two different FC CSP PoP solutions.
- With 800 million units shipped annually, and a good knowledge base and manufacturing capacity across the industry, innovations will continue to bubble up for this dynamic market.
- Different forms of PoP FO are being developed per conference presentations.
- Will processor and memory evolve in vertical stacking (as in PoP) or in side-by-side configurations? Will there be some hybrid format emerging?
PoP Development Trends
Examples of innovation and research in PoP-like architecture, process materials and manufacturing:

- “3D MiM (MUST-in-MUST) for advanced System Integration.” Au-Jhih Su et al (TSMC) ECTC 2019 and “3D Heterogeneous Integration with Multiple Stacking Fanout Package” Feng Cheng Hsu et al (TSMC) ECTC 2018.


Premier Phone Teardowns
Huawei P30 Pro
Samsung Galaxy S10 mmWave 5G
Shown above is the Huawei Pro30 Main Board Layout. Note the abundance of SiPs & FCCSPs

Above is the HiSilicon Kirin 980 in MCeP style PoP package with 1 mm mounted height. This remains the most common PoP configuration for advanced Smart Phones. The top packages are memory LPDDR4X with four die 60 um thick using gold wirebond 3L substrate 70 mm thick. The bottom application processor die, 75 um thick, has copper pillar bumps at 120 um pitch with capillary underfill. 2L upper substrate is 110 um thick, and 3L mSAP substrate is 115 um thick, 15 um L/S.
Samsung Galaxy S10 mmWave 5G (1)

Samsung S10 5G is first to the market with 5G mmWave. Most of the components are the same with addition of 5G baseband component, additional RF module and the antenna/tranceiver modules (which will be shown later).

- QCOM 855 AP/DRAM: FCCSP PoP
- Samsung UFS NAND: Wire bond stacked CSP
- QCOM 5G Baseband: FCCSP/wire bond DRAM
- QCOM RF Transceiver: FCCSP
- Qorvo PAD: SIP
- Qorvo PA: SIP
- Skyworks PAD: SIP
- Skyworks 2G PA: SIP
- Murata WiFi/BT: SIP

Samsung Galaxy S10 mmWave 5G (2)

The application processor uses MCeP style PoP structure for the Qualcomm Snapdragon 855 application processor. The twin wirebond memory packages are mounted over the lower application processor, which was flip-chip mounted over 3 layer Embedded Trace Substrate (ETS) 10 um L/S. The application processor die with Cu pillar 25 um height and 100 um pitch is thermal compression bonded over NCF underfill.

- 12.3 x 12.4mm MCeP® style PoP
  - 1.3mm height, with 4 die DRAM stack
  - Reduced substrate thicknesses
  - Samsung LPDDR4X with 8 (1GB) Die
  - Gold wire bonds
  - Die: 50μm thick; FOW: 50μm
  - 120μm EMC thickness over die

Processor Package
- 100μm thick die; 25μm Cu bump height
- TCB with NCP at <100μm pitch
- 4 capacitors (0402) between bottom solder balls
- 2L "Upper substrate": 100μm thick
- 3L Embedded Trace Substrate (ETS): 130μm thick, 10μm L/S, 55μm via diameter

Photo source: Prismark/Binghamton University
Leading Edge Materials and Technologies Implementation
as seen in recent smart phones (Apple iPhone 8)
Source: Prismark Partners October 2017

About 1000 Passives:
smallest 01005

Wireless Charging Coils

Nano Coating Material

Navigating 5G Challenges
Innovations & Collaborations
Antenna Module in Samsung Galaxy S10 mmWave (3)
Source: Prismark Partners

A. Front Facing 5G mmWave Antenna Module
- 4 patches and 4 dipoles
- 5GHz
- Connector for flex jumper to main PCB

B. Side Facing 5G mmWave Antenna Modules
- 4 patches
- 165mm
- Connector for flex jumper to main PCB

Qualcomm QTM 052 Antenna Module
Source: Prismark Partners

- Side Facing 5G mmWave Antennas Modules
  - 4 patches
  - 165mm module
  - Taconic substrate
  - Top 5 built-up layers for interconnect
  - Bottom 5 built-up layers for antenna

- mmWave Transceiver
- Patch Antenna
- Dipole Antenna (not in this module)
- Power Manager
- Power Inductors
- Connector for flex to main PCB
- Shielding
Mobile Front End Module Trend

Source: Yole

Antenna in Package Evolution

Source: Sheng-chi Hsieh (ASE) ECTC 2019
AiP Development Trend
Source: H Chang et al (ASE) IMS Boston June 2019

AiP Assembly & Package Overview
Source: H Chang et al (ASE) IMS Boston June 2019
AiP Substrate Stacking

Some Recent Technical Papers

- “InFO_AiP Technology for High Performance and compact 5G Millimeter Wave System”, CT Wang et Al (TSMC) ECTC 2018

- “Advanced Thin-Profile Fan-Out with Beamforming Verification for 5G Wideband Antenna”, Sheng-Chi Hsieh et al (ASE) ECTC 2019

- “Low-Loss Additively-Deposited Ultra-Short Copper-Paste Interconnections in 3D Antenna-Integrated Packages for 5G and IoT Applications”, Atom O Watanabe (GIT), Nabuo Oqura (Nagase) et al, ECTC 2019

- “Novel Multicore PCB and Substrate Solutions for Ultra Broadband Dual Polarized Antennas for 5G Millimeter Wave Covering 28GHz & 39GHz range” Trang Thai et al (Intel), ECTC 2019

- “Mm-Wave Antenna in Package (AiP) Design Applied to 5th Generation (5G) Cellular User Equipment Using Unbalanced Substrate” Ying-Wei Lu et al, ECTC 2018
Antenna Design Requirements

- Design for robust Beamforming and Directivity
- Shrink interconnections between die and antenna
- Low-loss and low-dielectric constant material
- Highly accurate process control
- Thermal dissipation design, materials and processes
- Design for Test

Mobile/Smart Phone: A Driving Force for Innovation

- As the dominant human-machine interface, Smart Phone, tablets and smart watches connected to high speed networks and the cloud will lead the industry in diverse applications in medical and health, industry IoT, finance, education and other fields that we cannot yet imagine.
- Smart Phones are made up of SiP/SiM Modules, leading the way for the continued innovation, sophistication, and implementation of Heterogeneous Integration Technologies across broader electronic applications.
- Smart Phone will be the platform driving and launching innovative technologies – 5G, AR, VR & AI – that will propel innovation and the proliferation of electronics in our world for many years to come.
- The Heterogeneous Integration Roadmap will play a significant role in bringing the ecosystem together to foster the spirit of innovation and collaboration.
Heterogeneous Integration for Mobile Networks

(see Chapter 2)

Heterogeneous Integration for Mobile Network Systems is covered in the High Performance Computing and Data Center Chapter. We have “borrowed” a few slides from that chapter to give a high-level view of the drivers, challenges and potential solutions.

We recommend that readers access that chapter’s full discourse on that topic.
Drivers for Heterogeneous Integration in the HPC/DC Segment

Source: K Ghose HIR HPC Data Center TWG

- **Die cost per unit area increasing** with node shrinks and refinements (hypernodes)
- **Package IO, latency/BW and power constraining single-die substrates**
  - It’s all about moving data!
  - Memory access bottlenecks limit single-chip solutions
- **Emerging applications demand domain-specific accelerators**
  - Analytics/Intelligence on demand
  - Big data processing
  - IoTs
  - Blockchain processing
- **Emerging processing paradigms, devices**
**Heterogeneous Integration Challenge Areas**

Source: K Ghose HIR HPC Data Center TWG

- On-package interconnections
- Off-package interconnections
- Signal integrity and distribution needs
- Power distribution and regulation
- SiP-level global power management
- Security and reliability issues
- Design and Test tools
- Supply chain

**Potential Solutions: A 60,000 feet View**

Source: K Ghose HIR HPC Data Center TWG

- Integration of accelerators, general-purpose processors, stacked memory (HBM, Stacked SRAM, MRAM) using 2.5D and/or 3D integration
  - Includes tessellated/tiled realization of computing chiplets
- Wide, short connections among chiplets (Silicon bridges, vias), in-package photonics for IO
- Aggressive signal encoding at all levels – intra-package, I/O
- Aggressive solutions for thermal management and cooling
  - SiP-level global power management
  - Thermal vias, dummy die with micropillars, conformal lids, water cooling, 2-phase cooling,…
- High-voltage power supply to package and package-internal distributed conversion to chip-level voltages
- System level tools for design and optimization
- Techniques for realizing secure solutions and graceful degradation
- Standards
  - CXL, ODSA, others and active interposers
- Integrated Si Photonics… and Others
Silicon Photonics Co-Package Integration
Source: John Shalf (LBNL) HIR Workshop at SEMICON West July 2019

High-Density fiber coupling array with 24 fibers = 6-12 Tb/s bi-directional = 0.75 – 1.5 TB/s

Silicon Photonics Co-Package Integration

5G Applications
Source: Yole Advanced RF System-in-Package for Cell Phone 2019 p57
Future Vision

Presentation “Mobile is the Future”
by Steve Mollenkopf Qualcomm CEO at ERI Detroit July 2019
Next-generation SoC design in the 5G era
Integrates with all package technologies

Silicon interconnect

Package RDL interconnect

Evolution of mobile design architectures
SoC + discrete RF/analog  Sub-system modules  System-in-package

Evolution of mobile form factors

Presentation “Mobile is the Future”
by Steve Mollenkopf Qualcomm CEO at ERI Detroit July 2019
The Next Big Phones Could Bring a Billion People Online

Bloomberg Business Week, 10 June 2019
by Shira Ovide

“Two of the biggest mobile operators in Africa – MTN Group & Orange SA – this year started selling quasi smart phones for as little as $20.” “Designed for 3G because 4G does not reach 2/3 of MTN’s 230 million customers”

“Africa has the worlds lowest share of people using internet, under 25%. The cohort of 800 million offline people spread across the continent’s 54 countries is younger and growing faster than most, but incomes are lower”.

“Boosting a poor country’s mobile internet use by 10% correlates with an average 2 percentage-point increase in gross domestic product”.

“Like energy and transportation, internet access has become an essential component of infrastructure, economic development and social empowerment”
Challenges
Mobile Network and Smart Devices: A Driving Force for Innovation

- Increased functionalities while retaining same form factor, battery life and user experiences
- Expanding affordability to broad global population: Broadband Internet access for all?
- Innovations to fulfill full potential of 5G
- Increased personal security across all phones 4G - 5G and Beyond 5G
- Synergy in 5G and Artificial Intelligence
- Global availability and sustainability

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