mmWave for Short-range communications

Challenges and Opportunities

Micky Mehta

Email: micky.mehta@pharrowtech.com

PHARROWTECH

Pharrowtech @SparkLink Alliance Meeting, 19-20 Nov '24

Listen, Understand and then Identify possible areas for contribution

- Pharrowtech – a brief introduction
  - Technology, Expertise & Products
- 60GHz band technology
  - The Past, The Present, The Future
  - Low-cost, Consumer Electronics
- Our current progress, achievements and plans

Recommend possible areas for SparkLink Alliance to consider and propose

- Q&As

Pharrowtech

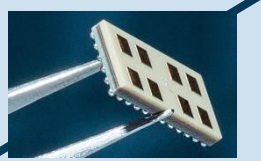
A Brief Introduction

Spin-off from imec, world-leading semiconductor R&D center

€7m Series Seed (2019) – €2m grants – €15m Series A (2022)

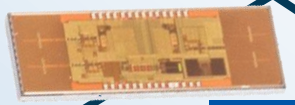
imec

2005
60 GHz R&D



2011
79 GHz
automotive radar

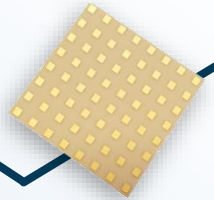
2015
140 GHz
consumer radar



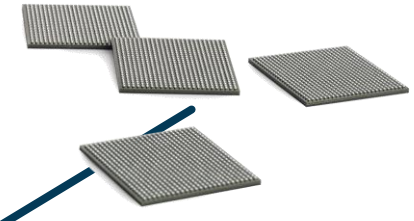
Panasonic

PHARROWTECH

2019
60 GHz
RFIC + antenna proof-of-concept
€7m Series Seed



2022
60 GHz
Production ramp
€15m Series A



Pharrowtech Platform Roadmap

Pharrowtech leads the next wave of high-speed wireless connectivity

IEEE 802.11ad/ay

mmWave 5G NR

IMMW Wi-Fi 8

FWA, back- and fronthaul, CCTV, industrial, automotive…

Fixed Wireless Access (FWA), consumer, wireless CCTV, wireless AR/VR…

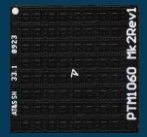
2024 2025 2026 2027 2028

IEEE 802.11ad/ay Platform

Products

PTR1060
RFIC & SW

PTM1060
RFM & SW

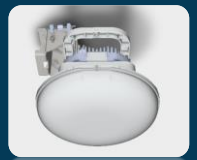


Reference Designs & Evaluation Kits

PTX1060
Wireless Module

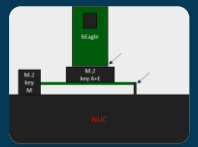
PTC1060
PtMP device

PTC1061
High-Gain device



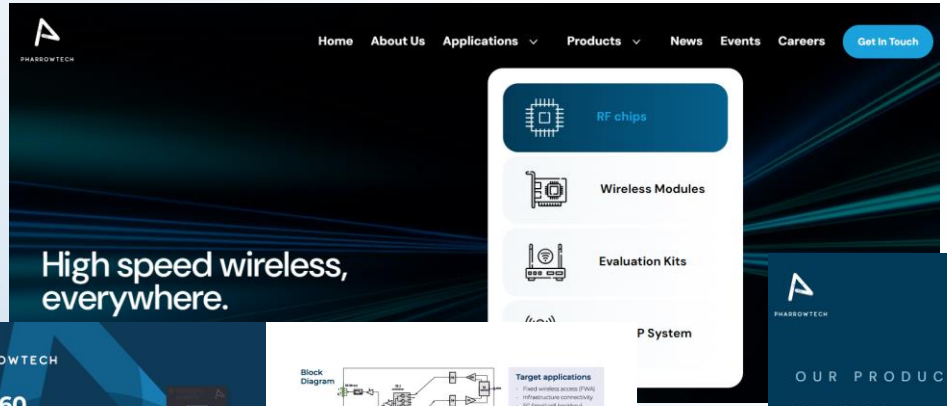
PTK1061
Evaluation Kit

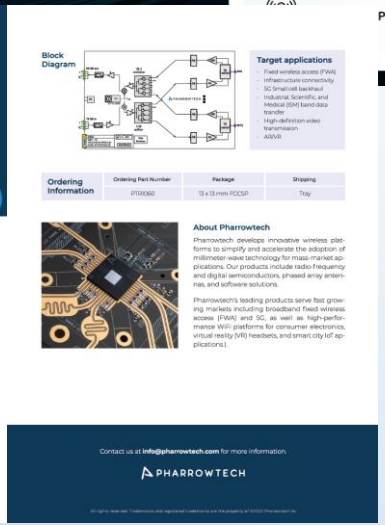
PTK1062
Wireless HDMI

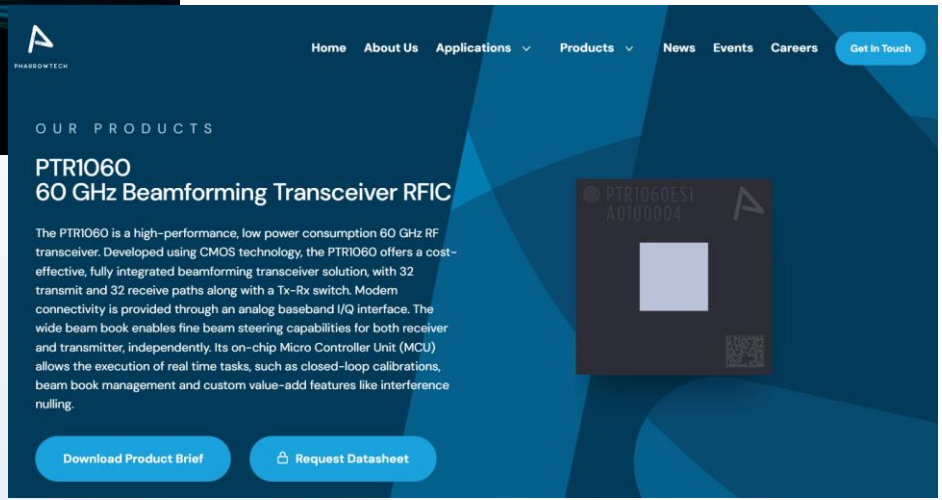


All product briefs available at https://pharrowtech.com/products/

Find product briefs and more at www.pharrowtech.com







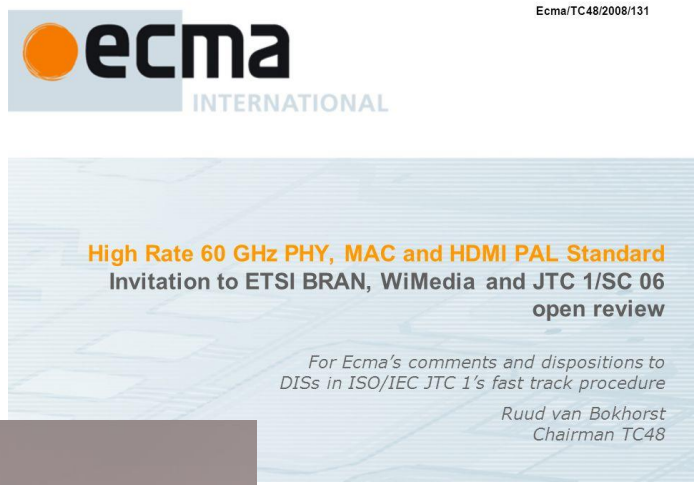
60GHz band unlicensed spectrum

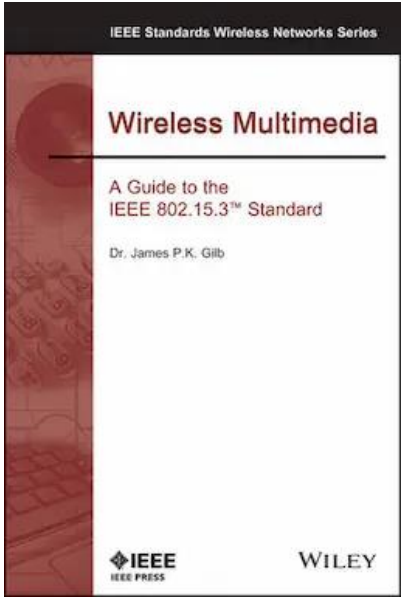
Historical perspective of 60GHz technology

The Past

60GHz band operation is a well trodden ground

- 802.15 TG3c
- ECMA
- WirelessHD





The Present

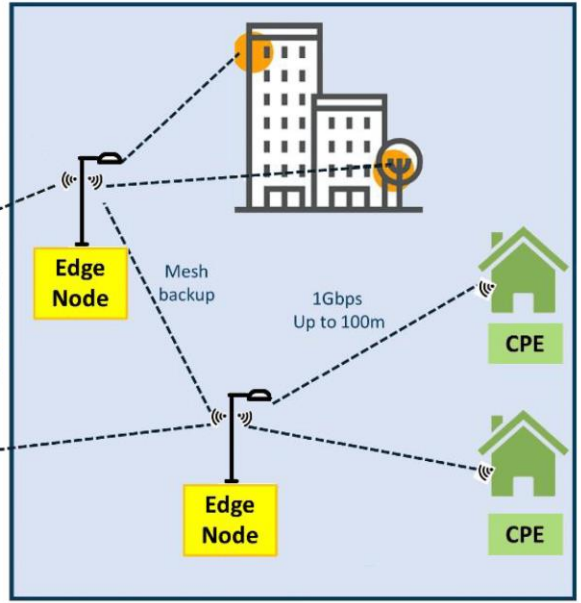
(E)DMG based 60GHz Fixed Wireless Access are popular with Wireless ISPs

Cambium Networks™

UBIQUITI NETWORKS

IgniteNet

Siklu



Tachyon Networks®

Fiber PoP / 60GHz IWF

Backhaul Node

Proxim wireless

Pharrowtech's current product address this market

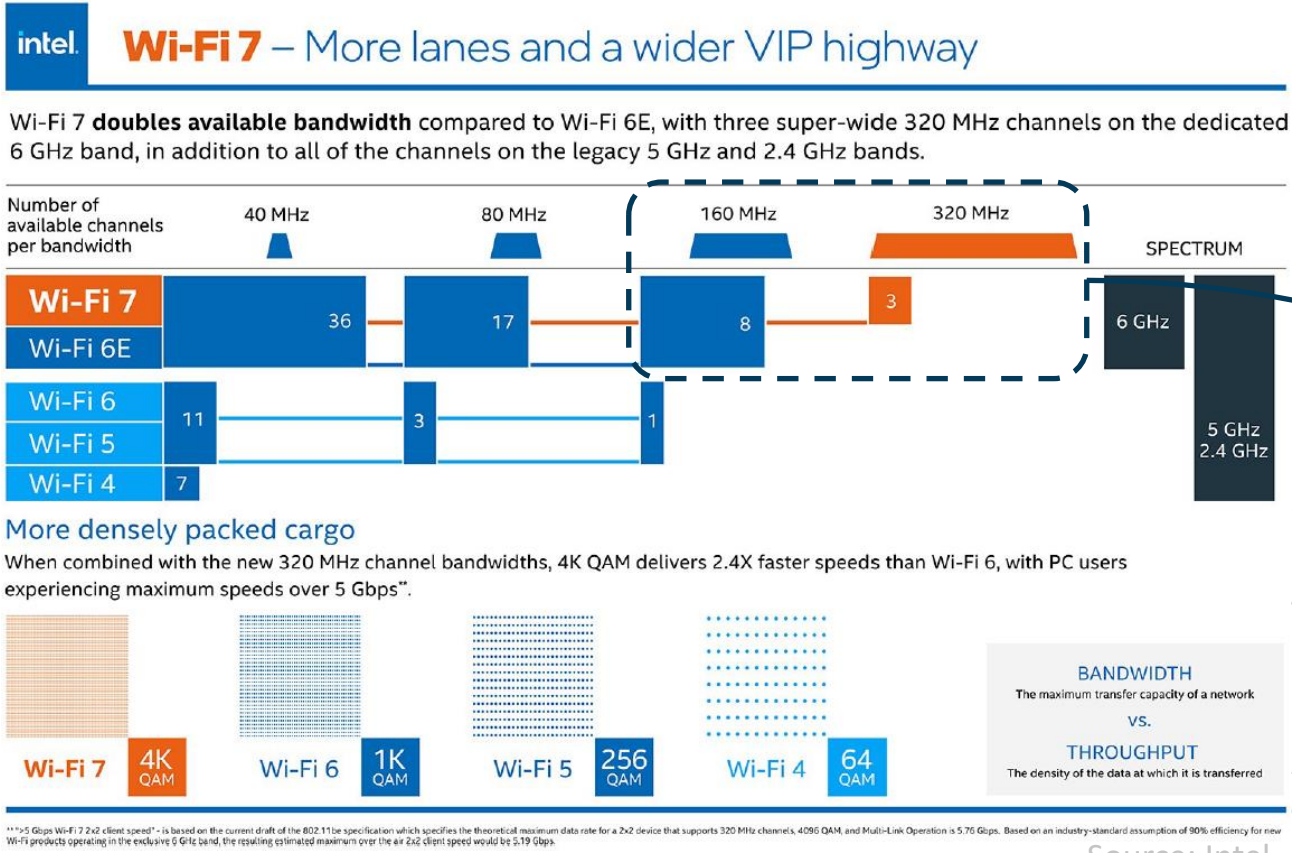
The Future

802.11 based Wi-Fi continues to dominate wireless data consumption

- Need >10Gbps data rate <u>with</u> low latency (deterministic) and reliability
  - Cloud AR/VR/XR; with pedestrian speed mobility
  - Industrial and Medical applications; time-sensitive
  - Real-time UHD video distribution, PBSS and infrastructure mode
  - Marked increase in Capacity (bps/Hz/m^2); increase user density and improved user experience
- Several new features are expected in next generation WLANs
  - Multi-AP Coord, Multi-Link Operation, wider channels (320, 480, 640MHz), UL MU-MIMO …
- Advances in MAC and PHY on their own are not adequate
  - Need many more wide channels (160MHz, 320MHz and wider) in relatively 'clean' spectrum
  - Multi-band support with appropriate in-built 'smarts' are necessary

> **<u>REQUIREMENTS</u>**
>
> ***High Throughput <u>and</u> Low Latency***
> ***<u>and</u> High Reliability***
> ***At Low Cost <u>and</u> Low Power***

Growing trend for wider channel bandwidths



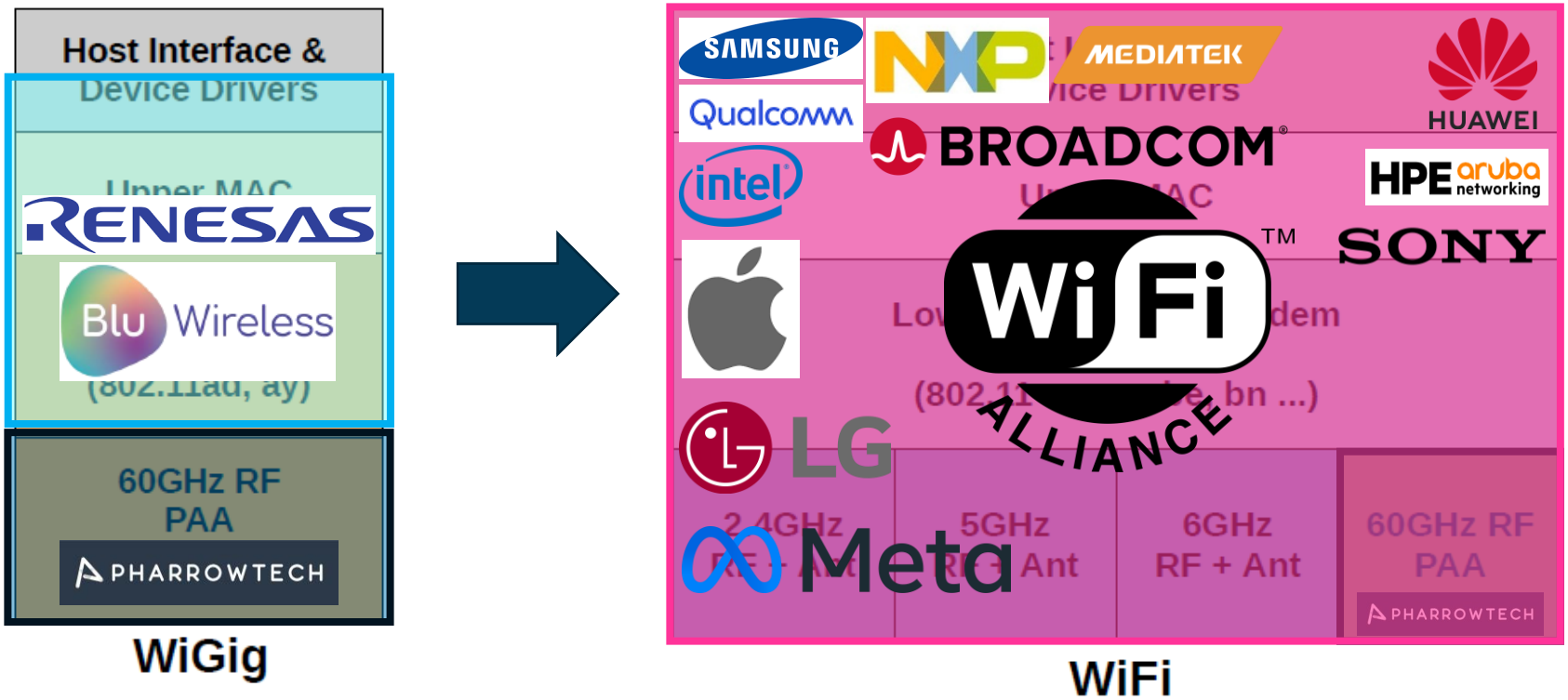
8 channels of 160MHz and 3 of 320MHz; all in 6GHz band are not sufficient for growing capacity for a diverse high t'put applications and need for deterministic provisioning

Need several wide channels; and 60GHz band is the obvious choice!

Source: Intel

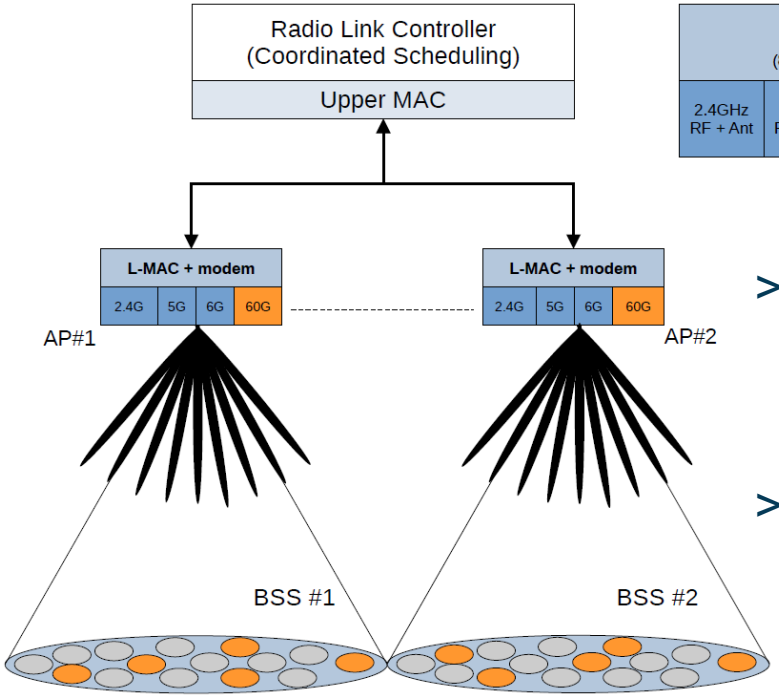
60GHz band support in Wi-Fi (1/2)

Must demonstrably steer away from (E)DMG protocol



60GHz band support in Wi-Fi (2/2)

Augment incumbent sub-7GHz networks to improve T'put, Reliability & Latency



> Multi-Link Operation facilitates addition of new RF band
  > Channel Access protocol to run across all RF resources
    > E.g., Discovery, Association, Schedule timings etc at sub-7GHz band?
  > Revised Scheduler to enable high throughput & low-latency
> Multi-AP Coordination helps reduce latency with roaming
  > Controlled Worst-Case Delay via AP coordination
  > Capacity management

Challenge for SparkLink Alliance to identify compelling use-cases & deployments above and beyond those considered in Wi-Fi

60GHz band unlicensed spectrum

Technical Challenges

Technical challenges with mmWave band(1/2)

PHY System design & architecture considerations

- RF impairments at mmWave are markedly pronounced (worse) than that at sub-7GHz
  - XTAL ppm spec – CFO, jitter, SFO
  - Phase Noise – must keep integrated phase noise within loop bandwidth of phase tracking loop
  - Noise Figure – must be as low as possible
  - Quadrature Mixer & LO distribution – IQ imbalance (frequency selective?)
  - Direct conversion or not – is input analogue baseband (zero-IF) or low-IF (e.g., 6GHz modulated RF)?
  - DC offset and Carrier feed-through – impact on Tx spectral mask and Tx EVM
  - Analogue filtering – gain flatness, group delay, phase response
  - PA nonlinearity – OFDM PAPR will be high – need some pre-distortion and/or crest factor reduction
- OFDM subcarrier spacing, CFO tolerance, gain flatness and impact on equalization
  - Flexible numerology (akin 3GPP) – impact on DSP implementation complexity, refinement and related PLL design etc
- Channel raster considerations – channel spacing and channel bandwidth
  - Support 20MHz, 40MHz and 80MHz channel or just target 160MHz, 320MHz and 640MHz channel bandwidths
  - Integer or Fractional-N PLL/SYNTH?
- Array Processing and Beamforming – codebook derivation, precision and complexity
  - fully or partially connected, IF and RF precoder design, AP, STA asymmetric antenna array & Link margin
- DSP requirements – numerical precision, ADC/DAC specs, clock tree, power management etc

Opportunity for SparkLink Alliance to establish appropriate requirements

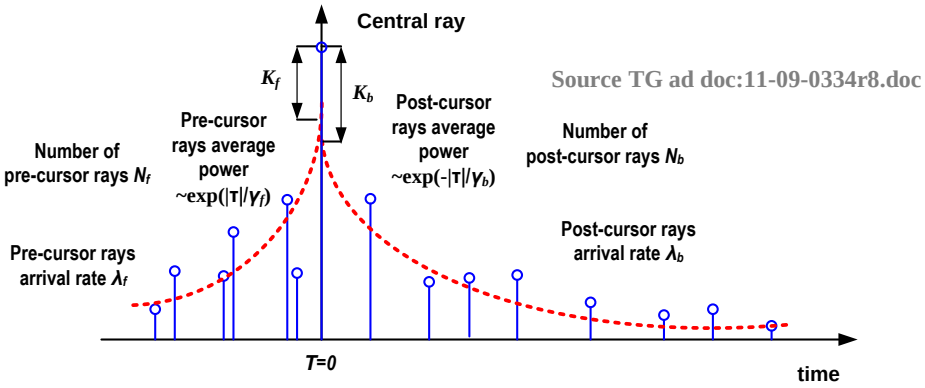
mmWave RF Front-end development (2/2)

… beyond PHY layer topics

- MLO and related topics – AP MLD and non-AP MLD scheduling (Beacon etc)
  - Multi-Link Multi-Radio, Enhanced Multi-Link Multi-Radio
  - Additional functions and need to expose needed APIs for mmWave extensions
- Coexistence with 60GHz radar, WiHD, (E)DMG, 802.11bf, 802.11aj …
  - Unlicensed band operation means plausible coexistence protocols
- Control interface considerations and module management
  - Real-time software development to regulate functionality, performance & behaviour of RFM
- Silicon & Module level considerations
  - Mitigate PVT variabilities, Module Thermal properties, Cost etc

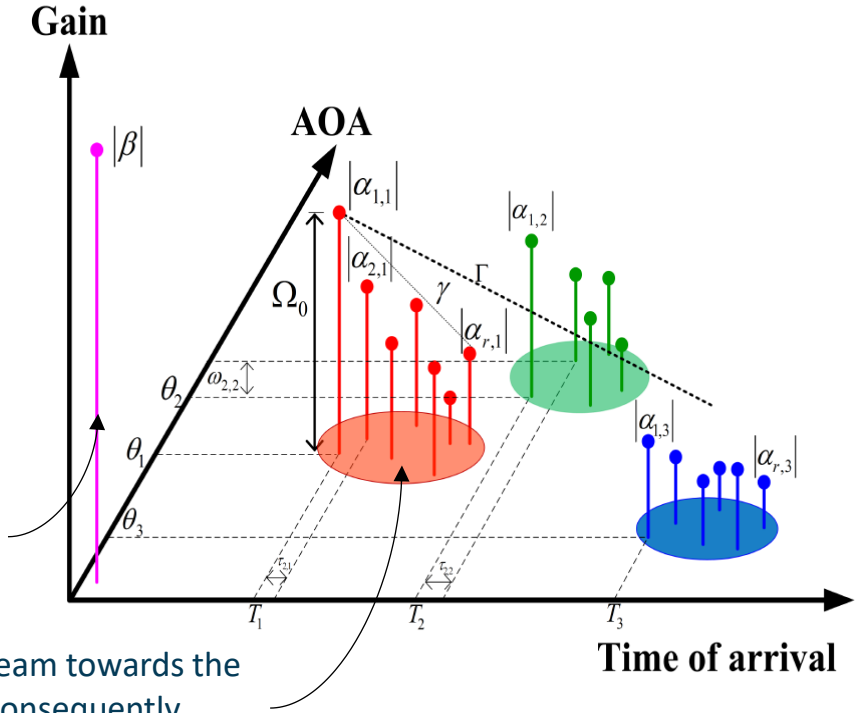
60GHz Indoor propagation channel (1/2)

Clustered Impulse Response – LOS (dominant) and NLOS (cumulatively significant)



Source TG ad doc:11-09-0334r8.doc

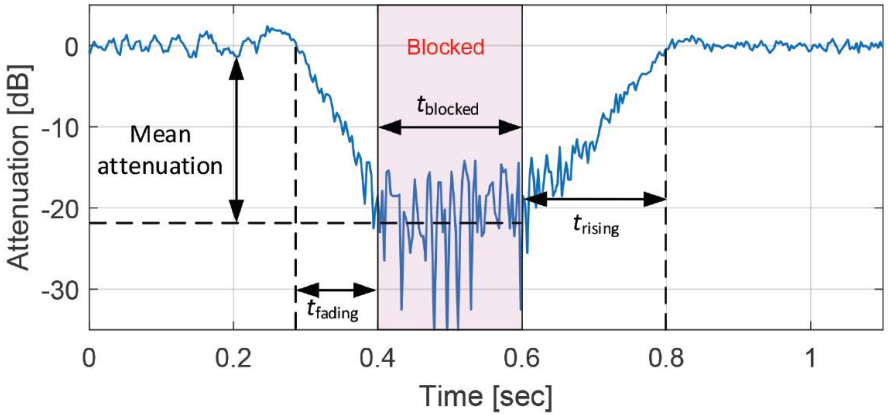
Beamforming will converge Tx & Rx beam towards the LOS cluster. Typically, high SNR and consequently high MCS support

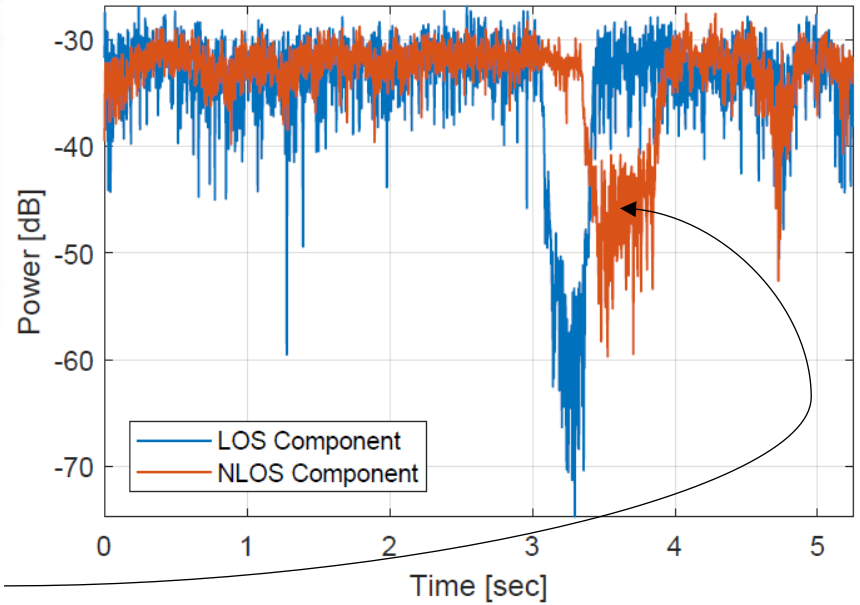


But in NLOS conditions, beamforming will converge Tx & Rx beam towards the NLOS clusters, one that yields the best SNR (not Rx power). Consequently, low-moderate SNR is observed and corresponding low MCS support

60GHz Indoor propagation channel (2/2)

Measurements and Analysis @ NYU WIRELESS, Brookyln, NY 11201, US





NLOS clusters' attenuation is less severe than that of LOS; due to transient blockage

Pharrowtech Roadmap

Target Products

Our position on mmWave Wi-Fi

Collaborate to develop a Compliant RF silicon, module & software

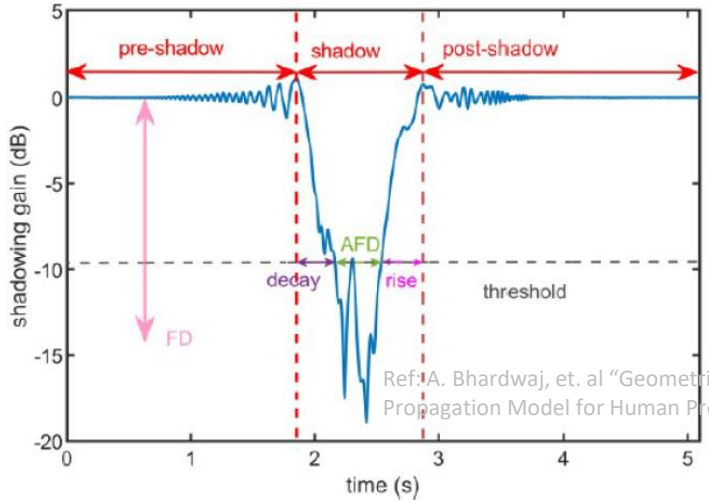
- Pharrowtech plans to develop enabling technology with Partners & Alliances
  - Be thought leaders in mmWave RF Front-end **technology and products**
  - Benefit from the renewed interest in 60GHz band, e.g., Task Group 'bq' in 802.11 standards
  - Participate in relevant standards' development together within an established ecosystem

- The '3rd coming' of 60GHz should be an Integrated feature of next gen Wi-Fi
  - Alike 2.4GHz, 5GHz and 6GHz band, 60GHz would be yet another RF band to operate
  - Self-contained mitigation against pronounced RF impairments and hostile propagation channel
  - Leverage expertise gained from developing RFIC (PTR1060) and RFM (PTM1060)

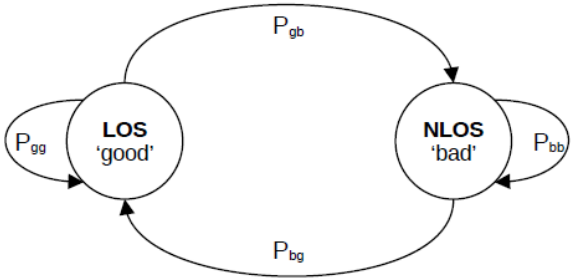
- Promise of large swathes of spectrum in 60GHz, on its own, is not sufficient
  - Solution must perform as well as 5GHz and 6GHz bands, for the same channel width
  - At an attractive Power, Area and Cost

mmWave band transmission - an ***auxiliary*** option (*1/2*)

Channel-aware data transmission to maximise T'put, Latency and Reliability



Ref: A. Bhardwaj, et. al "Geometrical-Empirical Channel Propagation Model for Human Presence at 60 GHz", IEEE, 2020



P_{gb} = probability to transit 'good' state to 'bad'

P_{bg} = probability to transit 'bad' state to 'good'

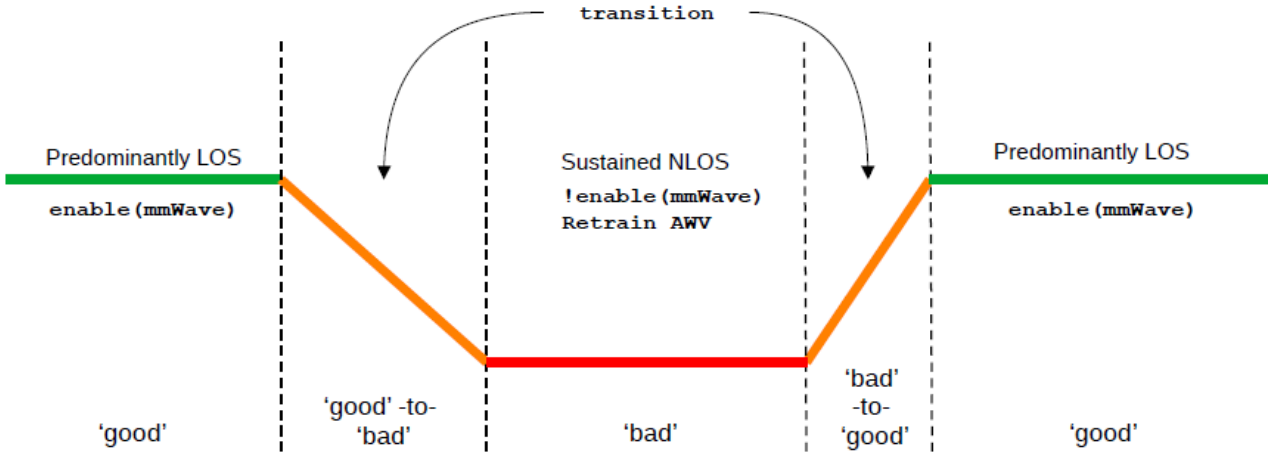
P_{gg} = probability retain 'good' state to 'good'

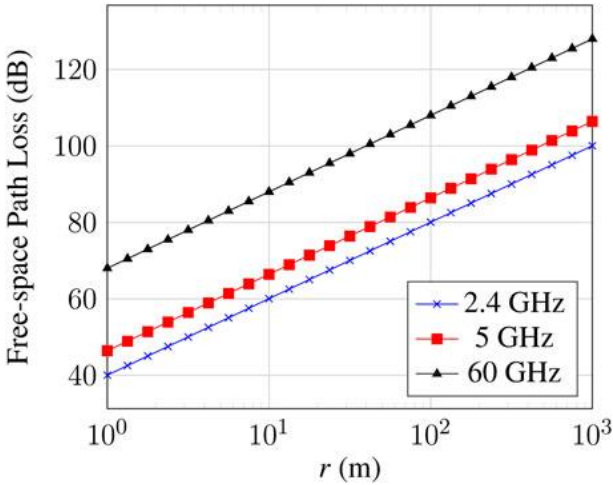
P_{bb} = probability retain 'bad' state to 'bad'

- mmWave propagation is severely limited by signal shadowing; particularly so in Indoor environments
  - Results in near continuous changes in Link Adaptation, protocol frame fragmentation and eventually, bursty throughput
  - Not suitable for sustained (steady) throughput real-time applications with minimum jitter, e.g., video
- And so, only use mmWave when conditions are 'good'; switch in/out of mmWave transmissions
  - Revert back to sub-7 GHz transmissions when channel-state is not adequate

mmWave band transmission - an ***auxiliary*** option (*2/2*)

Channel-aware scheduling – Markov 2-state model



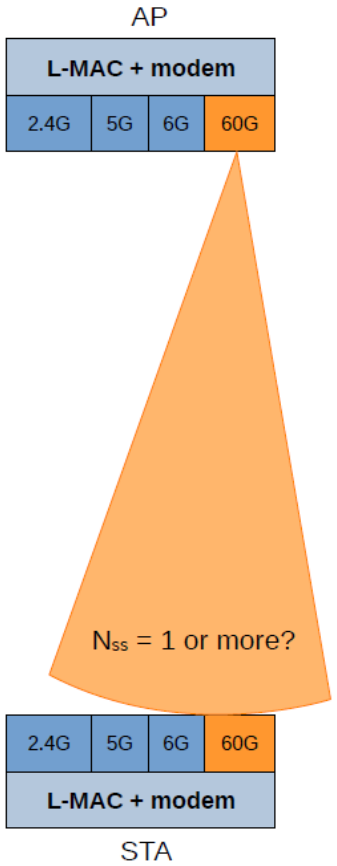


> Devise extensions to the MAC scheduler to traverse between mmWave and sub-7GHz modes
  > Multi-dimensional cost function to determine when to 'enable' mmWave transmissions and when not to
  > MLO functions to facilitate necessary administration
  > Periodic antenna weights vector retraining to establish new/revised codebook; possible use of ML concepts

Beamforming in the context of 60GHz band transmission

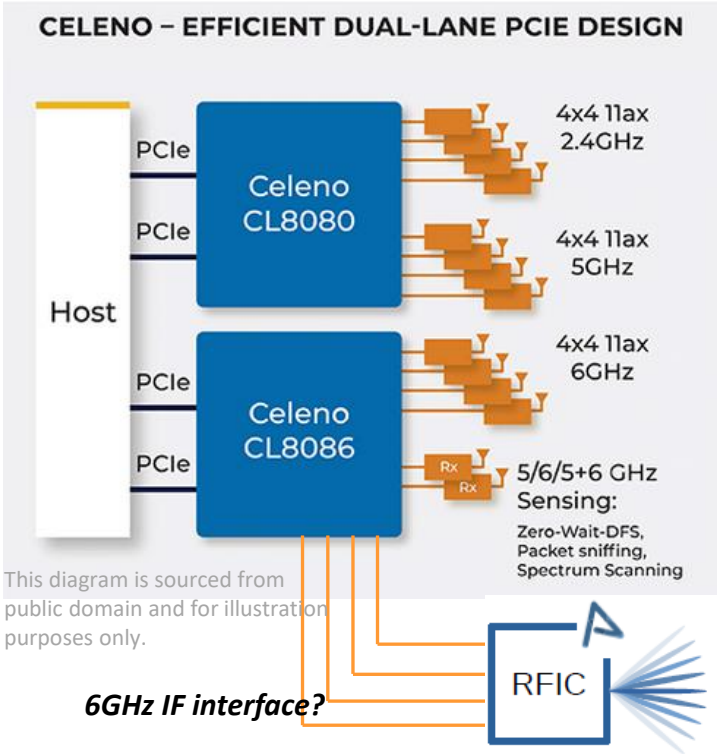
A different approach is needed to meet different requirements

- Need for Beamforming in 60GHz band is well understood
  - Analogue Beamforming is an integral part of (E)DMG Channel Access
    - Essential to meet realistic Tx power and secure reasonable link budget
    - Antenna weights yield coherent combining a desired spatial direction
      - Pencil beam means a collapsed rank of the MIMO channel matrix
  - Digital Beamforming is not practical in (E)DMG
    - Wide channel bandwidths, realistic ADC/DAC sample rates, power consumption
- Focus on OFDM waveforms
  - Upclocking 802.11ac and 802.11be modems is one obvious approach
    - But there is an opportunity for SparkLink Alliance to offer alternatives
  - Need to retain some statistical richness in the MIMO channel matrix
    - Coherent combining through Analogue Beamforming is detrimental
- *Answer: 'Self-healing Beamforming' (patent pending)*
  - *Novel solution from Pharrowtech*



An illustration of mmWave RF Front-end Module

'Smart' RF front-end module – targeting 802.11 WG Task Group 'bq'



This diagram is sourced from public domain and for illustration purposes only.

- Augment Wi-Fi air-interface with a mmWave module
  - 'Smart' 60GHz RF front-end module to turbo-boost transmissions
    - Self-contained beamforming solution; unlike (E)DMG
    - MLO functions to co-operate with sub-7GHz bands
    - 'Deterministic' scheduling to improve T'put, Latency and Reliability
  - Provision of many more 160MHz, 320MHz and wider CBWs
  - In-line with 802.11 standards (TGbq) and WFA compliant
- Attractive value proposition
  - Co-development with partner's Wi-Fi Digital SoC
    - Joint specs on data-path and control-path integration
  - Leverage incumbent expertise in 60GHz CMOS RFIC solutions
    - Proven RFIC, and RF module with integrated Phased Array Antenna
- *TGbq time-scales are protracted; will be after TGbn*
  - *Could SparkLink standards' mmWave development race ahead?*

Development Milestones

Leverage existing RFIC, Engage with Partners, Follow Standards

- #M1: Proof-of-Concept Demonstrator
  - Leverage existing SPIRIT transceiver module, PTB1060 (EVB)
    - Trial incumbent 802.11ac ($\Delta_{F,\ Pre\text{-}EHT}$ = 312.5kHz) waveform
    - Upclock 802.11ac; Ref: UHR SG doc: 1884r0, “mmWave Operation in UHR”, Intel et. al, 2022
  - Use Test & Measurement equipment for compliant Signal Source and Analysis
    - Experimental setup for further exploration and interactions with Partners
    - Complementary with ongoing Wireless System Architecture development towards design specs

Available today

- #M2 : ‘Smart’ mmWave RF front-end module
  - New RFIC + Antenna module to meet 802.11 WG Task Group bq requirements
    - Additional onboard DSP (digital ASIC) for self-healing beamforming and other functions
  - Will require close inter-working with Digital SoC partner
    - Upclocking 802.11ac and/or 802.11ax/be modem
    - MCS up to 64QAM is a must
    - Datapath (I/Q) and Control-path features and functions
    - Power consumption, Clocking, Package, Time-scales, Cost – the usual product dev constraints

SparkLink Requirements?

In progress

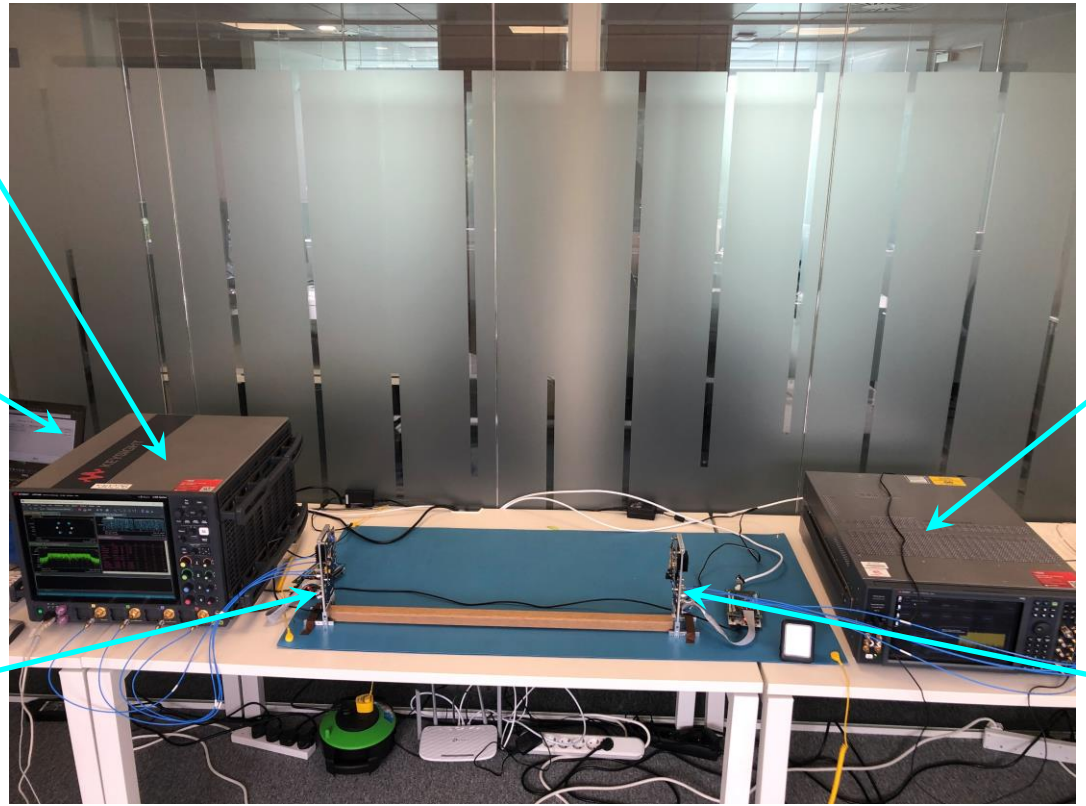
PoC Setup with Keysight Equipment

60GHz transmission of 802.11ac waveform across PTB1060 (SPIRIT RFM) modules

High-end Scope
- UXR033B

Signal Analysis s/w
- VSA 89601C

PC to run f/w (drivers)
- RF Calibration
- RF parameters



WiFi Signal Generator
- VXG-B, M9384B
- Signal Studio s/w N7617C, N7608C

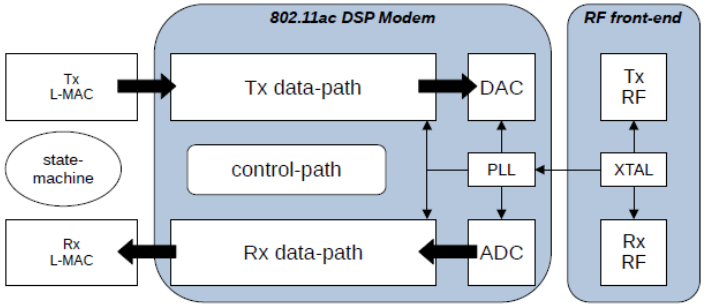
PTB1060 (Rx)

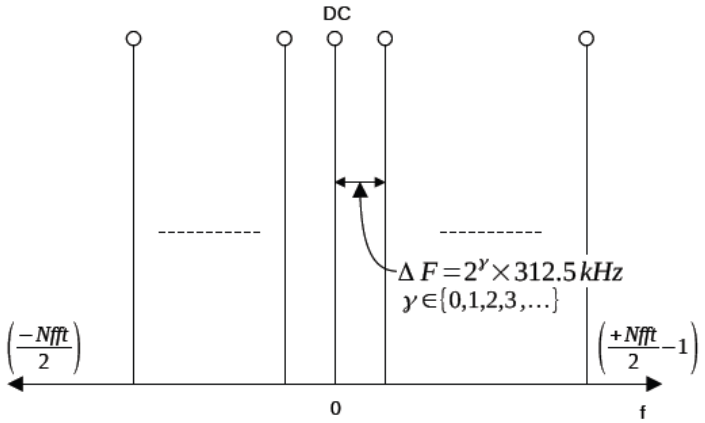
PTB1060 (Tx)

Upclock existing 802.11ac modem (Digital SoC)

Increasing subcarrier spacing beyond 312.5kHz dilutes 60GHz RF impairments

- Explore upclocking options T&M equipment
  - What should be the value of γ?
    - Larger γ will yield better immunity against some RF impairments, but will increase ADC/DAC power consumption and consume more RF bandwidth
    - And so, strive to achieve the best EVM for the smallest value of γ.
  - What are the effective RF impairments of PTR1060?
  - Measure Tx EVM and overall Link (Simplex) PHY performance
- Identify relevant topics for a realistic Digital SoC
  - 'Locked clock architecture' and related particulars
    - Overall clocking architecture, PLLs and jitter tolerance
    - ADC and DAC dynamic range, AGC operation
  - Control-path and interfaces between RF & Modem
    - RF front-end is typically a 'slave' to the 'master' Digital SoC
    - Dependency on timers and other control signals that regulate the RF front-end





Structured experiments – scope and definitions

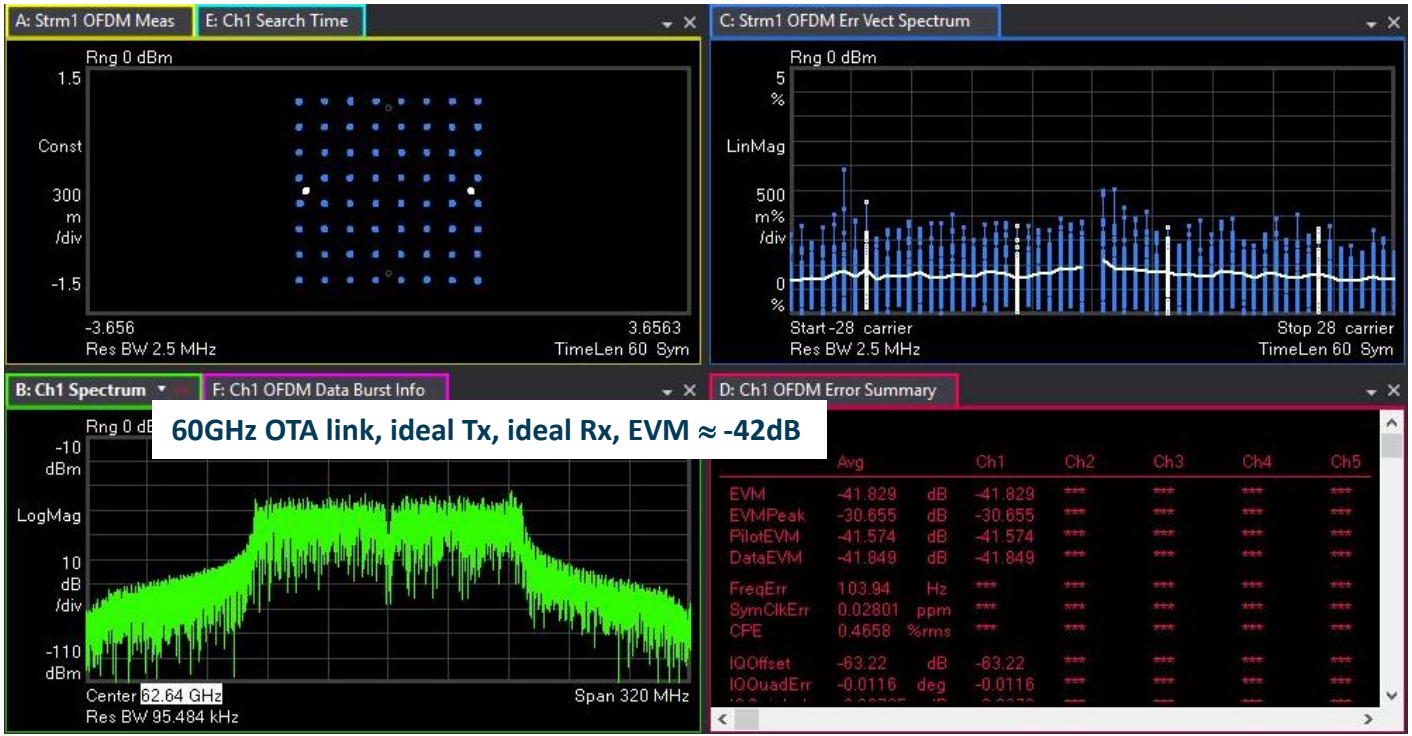
802.11ac waveform, CBW: 160MHz vs [20MHz **x8**] (**γ=3**)

Measurements	Tx	Rx	Notes
✓ Set-1	Ideal RF front-end (T&M)	Ideal RF front-end (T&M)	This will help establish the target performance that we should strive for. Obviously, our EVBs will never match the same from T&M instrument, but it should help steer our design priorities
Set-2	Ideal RF front-end (T&M)	PTB1060 (EVB) and Baseline 1.x software	This will help establish performance floor if all impairments are just at the Rx end
✓ Set-3	PTB1060 (EVB) and Baseline 1.x software	Ideal RF front-end (T&M)	This will help establish Tx EVM; which is one of the KPIs for inter-operability and compliance
✓ Set-4	PTB1060 (EVB) and Baseline 1.x software	PTB1060 (EVB) and Baseline 1.x software	This should yield OTA (over-the-air) link performance for candidate settings on the Tx and Rx EVBs, respectively. Scope for calibration and parameter setting here is large

- Separately, a body of work has been done to refactor the RF driver s/w and Calibration routines
- Each combination of driver s/w and optimized Cal parameters are grouped into Baseline 1.x named releases. Currently, we are at Baseline 1.3

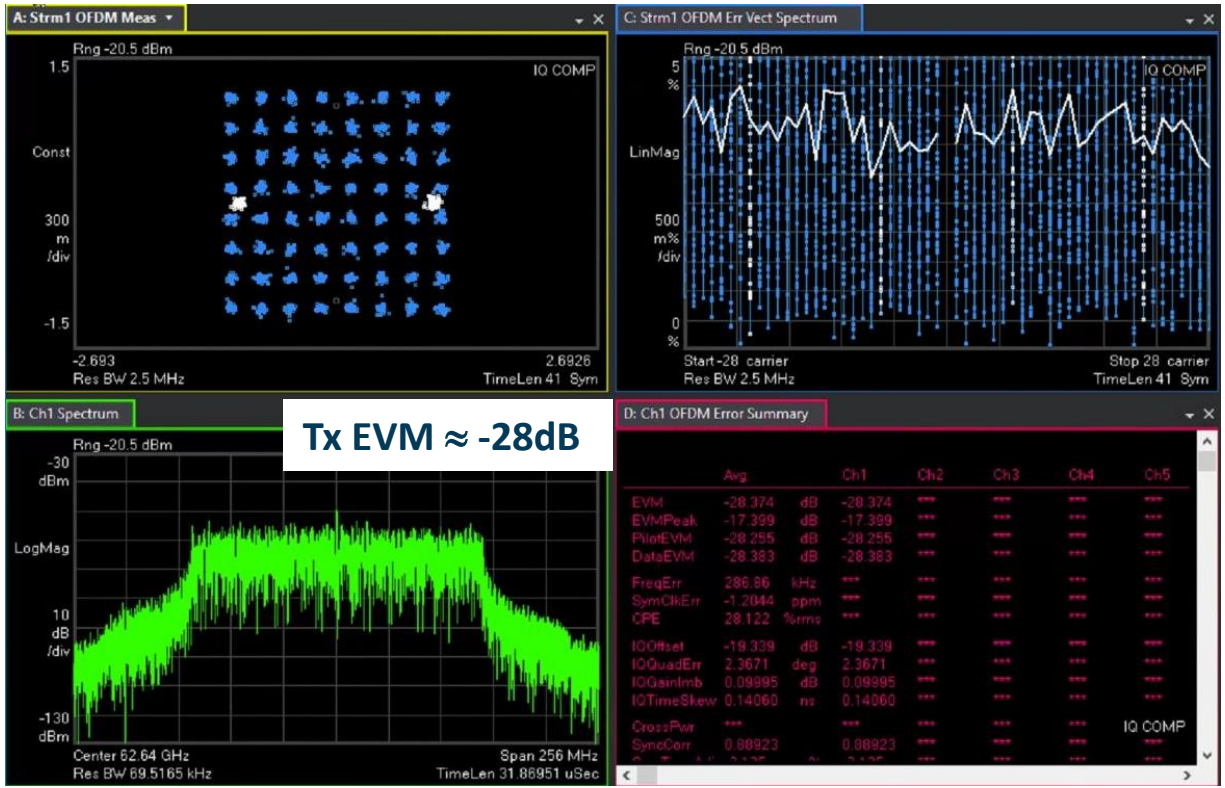
Set-1, Tx = [VXG-C + V3080a], Rx = [UXR scope, 110GHz], Keysight

802.11ac waveform, MCS5 (64QAM), CBW = 160MHz



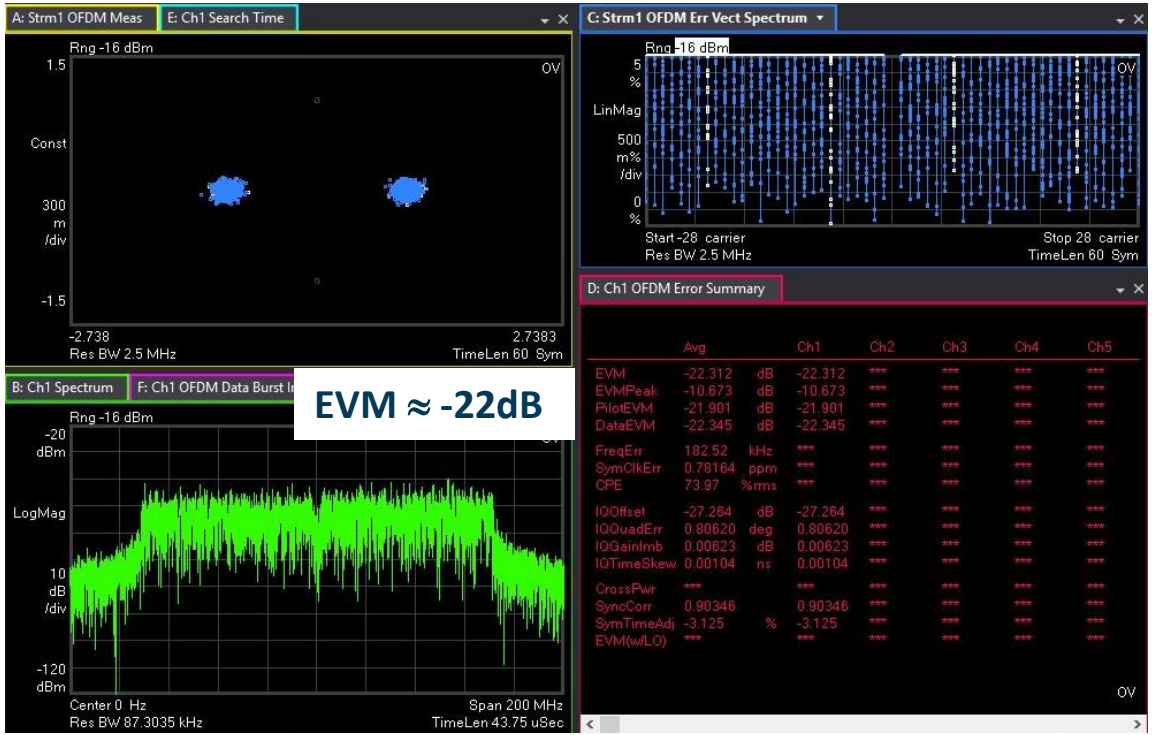
Set-3, Keysight instruments

802.11ac waveform, MCS5 (64QAM) CBW = 160MHz, [20MHz **x8**] (**γ=3**)



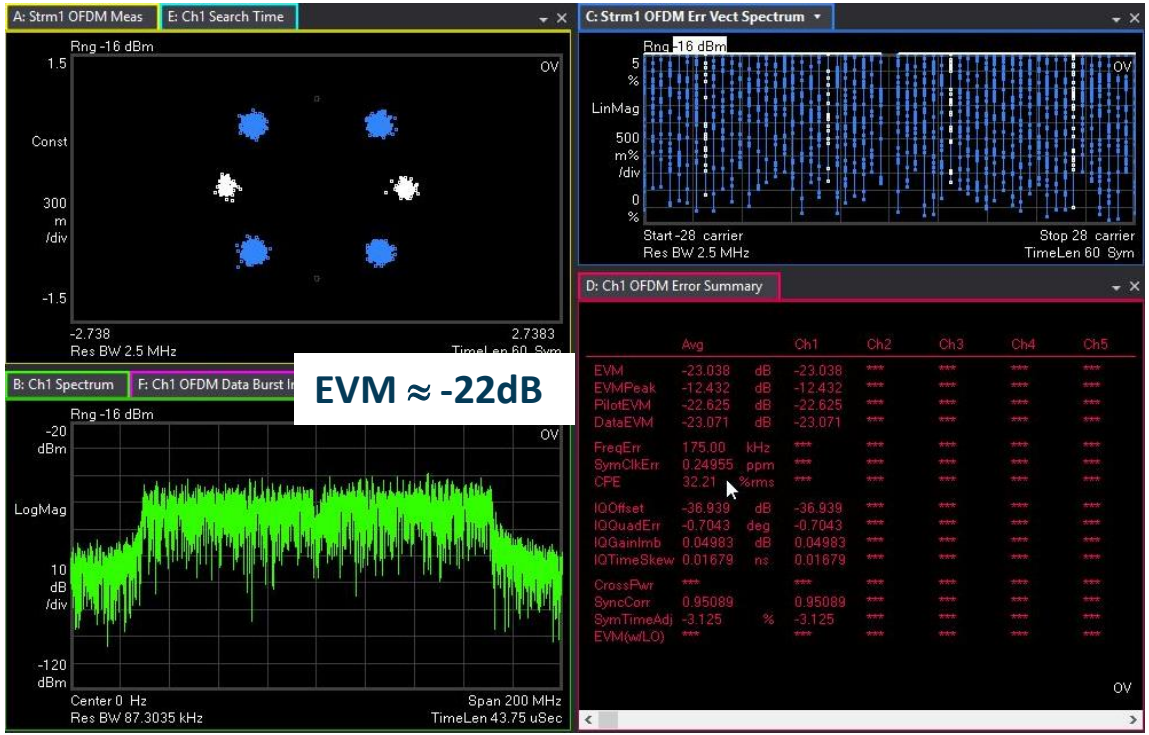
Set-4, Keysight instruments

802.11ac waveform, MCS0 (BPSK) CBW = 160MHz, [20MHz **x8**] (**γ=3**)



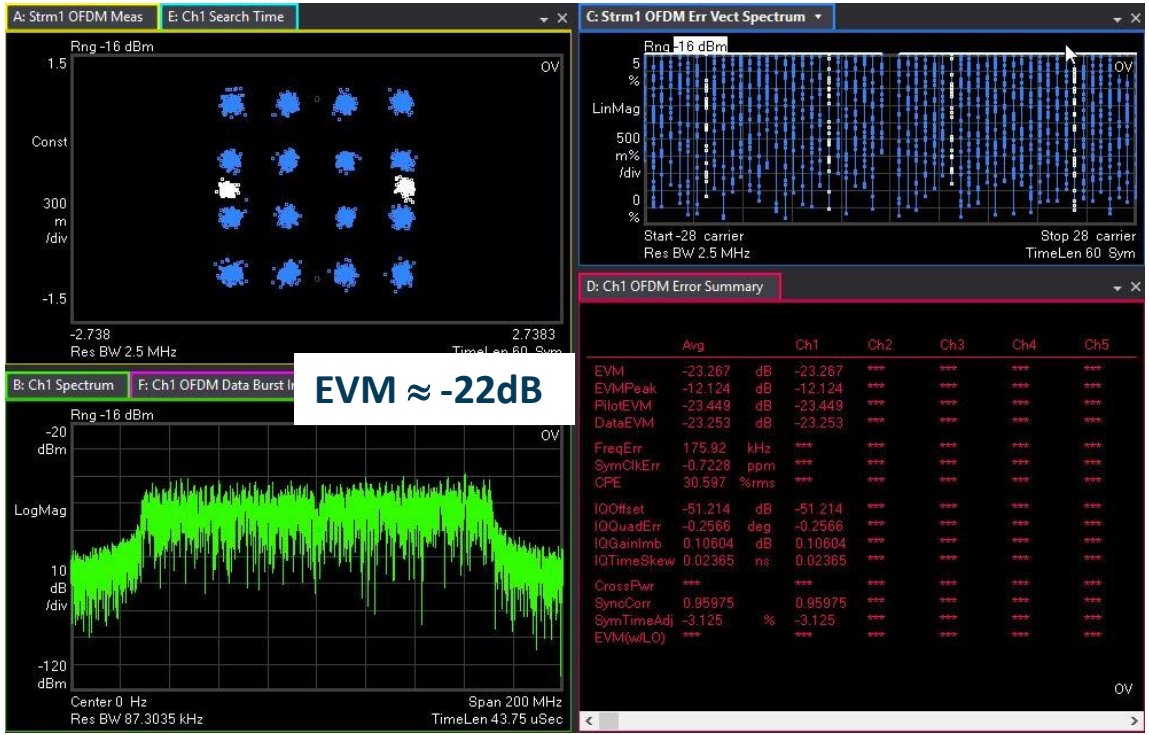
Set-4, Keysight instruments

802.11ac waveform, MCS1 (QPSK) CBW = 160MHz, [20MHz **x8**] (**γ=3**)



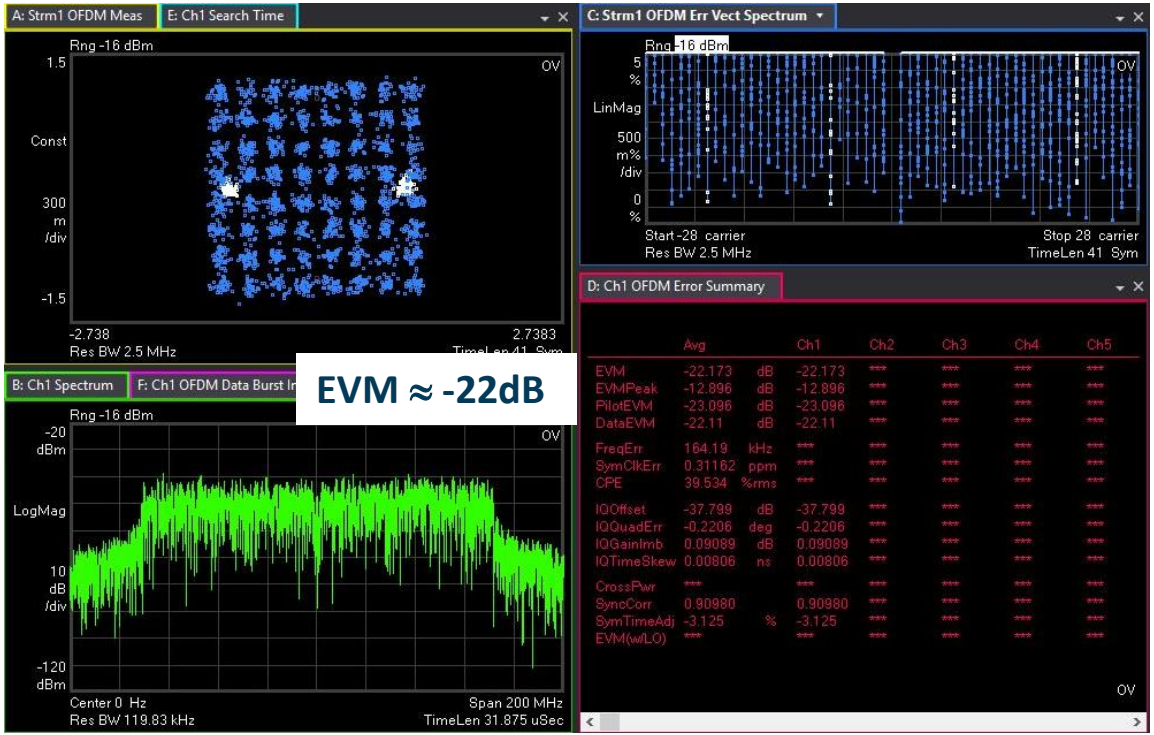
Set-4, Keysight instruments

802.11ac waveform, MCS3 (16QAM) CBW = 160MHz, [20MHz **x8**] (**γ=3**)



Set-4, Keysight instruments

802.11ac waveform, MCS5 (64QAM) CBW = 160MHz, [20MHz **x8**] (**γ=3**)



Latest results

802.11ac waveform, CBW: 160MHz vs [20MHz x8] (γ=3)

Measurements	Tx	Rx	EVM and notes
✓ Set-1	Keysight VXG-C + V3080a	UXR (110GHz)	EVM = -42dB
Set-2	Ideal RF front-end (T&M)	PTB1060 (EVB) and Baseline 1.x software	TBD
✓ Set-3	PTB1060 (EVB) and Baseline 1.x software	UXR (110GHz)	EVM ≈ -28dB
✓ Set-4	PTB1060 (EVB) and Baseline 1.x software	PTB1060 (EVB) and Baseline 1.x software	EVM ≈ -22dB with Baseline 1.3 configuration

- EVM observations are stable and proven to be so with nightly tests
- But there is room for further improvement
  - Alternative calibration, Tx & Rx gain line-ups and PA OBO
  - Need to analyze impact of Phased Array Antenna to overall channel impulse response

Future development plans at Pharrowtech

Outlook for next 1-2 years

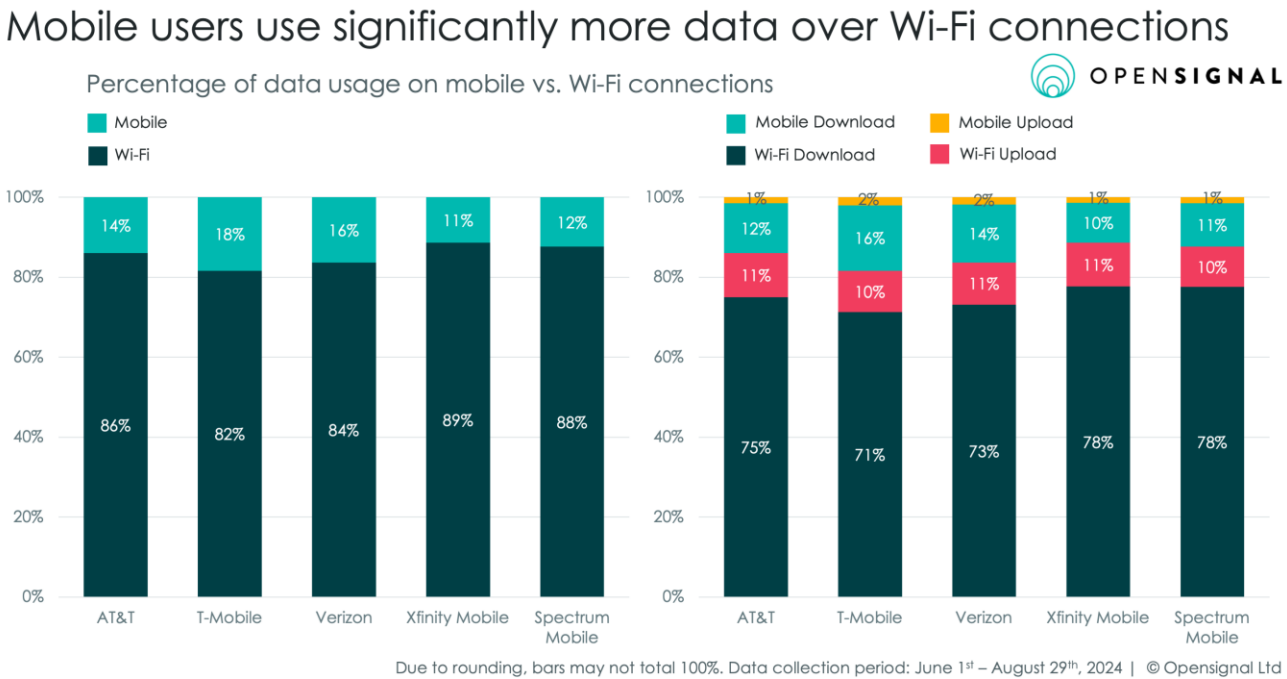
- Secure a working partnerships with a Digital SoC vendor
  - Jointly develop relevant enabling technology
    - Derive common requirements benefiting both companies
    - Healthy interaction between respective engineering teams
  - Agree on mutually acceptable time-line, target end-customers, products and so on
    - Commercial and Technical value proposition
- Evolve & improve the current PoC and its constituents
  - Optimize performance of incumbent PoC platform
  - Extend support for alternative OFDM modems, e.g., 802.11be (narrower sub-carrier spacing)
  - Consider and trial alternative air-interfaces and waveforms

Given the right commercial motivation, Pharrowtech would consider trialing alternative waveforms on its PoC platform. And that could be the basis for further specification to integrate a complementary Digital OFDM modem

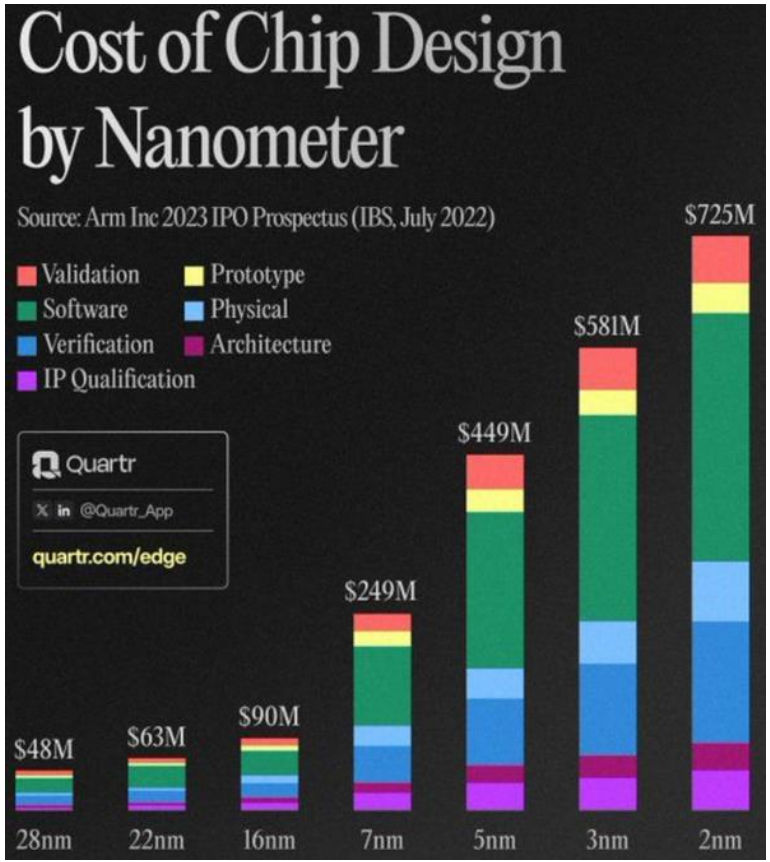
Pause for thought

SparkLink must have an unambiguous market ambition

What % of future data consumption (across different use-cases) over SparkLink connections



Commercial challenges often out-weigh Technical ones



E.g. Power & Area challenges are pushing chip vendors to smaller geometries. But this drives up development costs, mask/fab costs, time-2-market is pushed out …

SparkLink should facilitate an eco-system

- *Equipment Manufacturers (end-user)*
- *Chipset Vendors (critical components)*
- *Module manufacturers (ODMs)*
- *3rd party Software products*
- *Inter-operability, Compliance, Regulations*
- *…*

Questions & Comments