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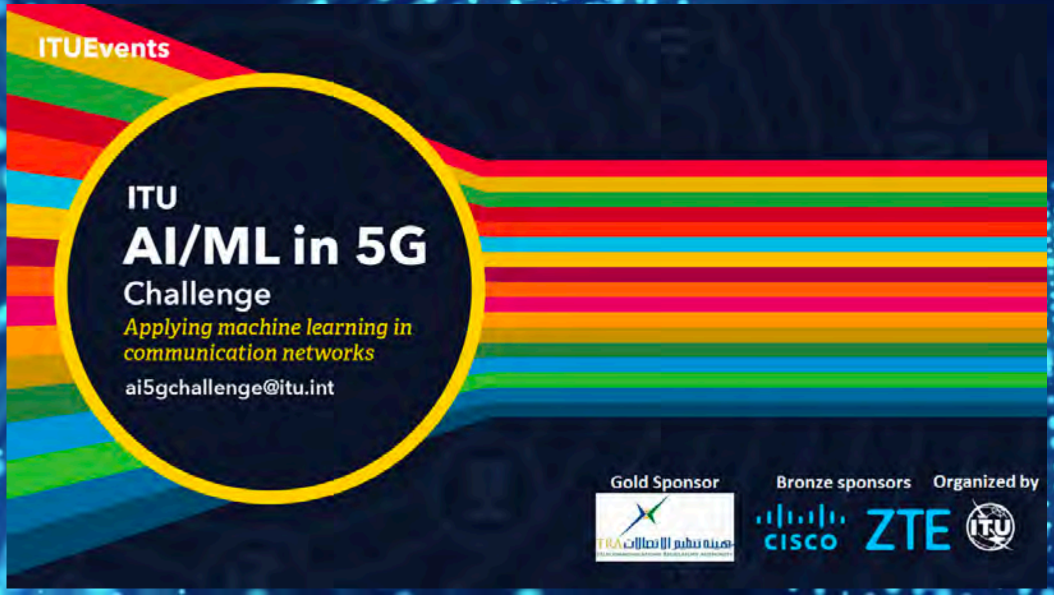

Leveraging AI & Machine Learning to Optimize Today's 5G Radio Access Network Systems and to Build the Foundation of Tomorrow's 6G Wireless Systems

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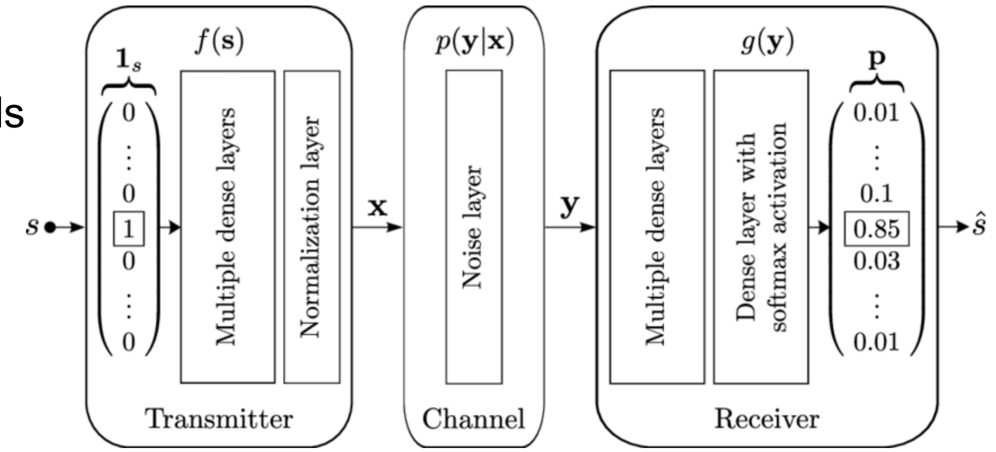
Massive Device Density in 5G, 6G, IoT, NB-IoT, WLAN, LPWAN

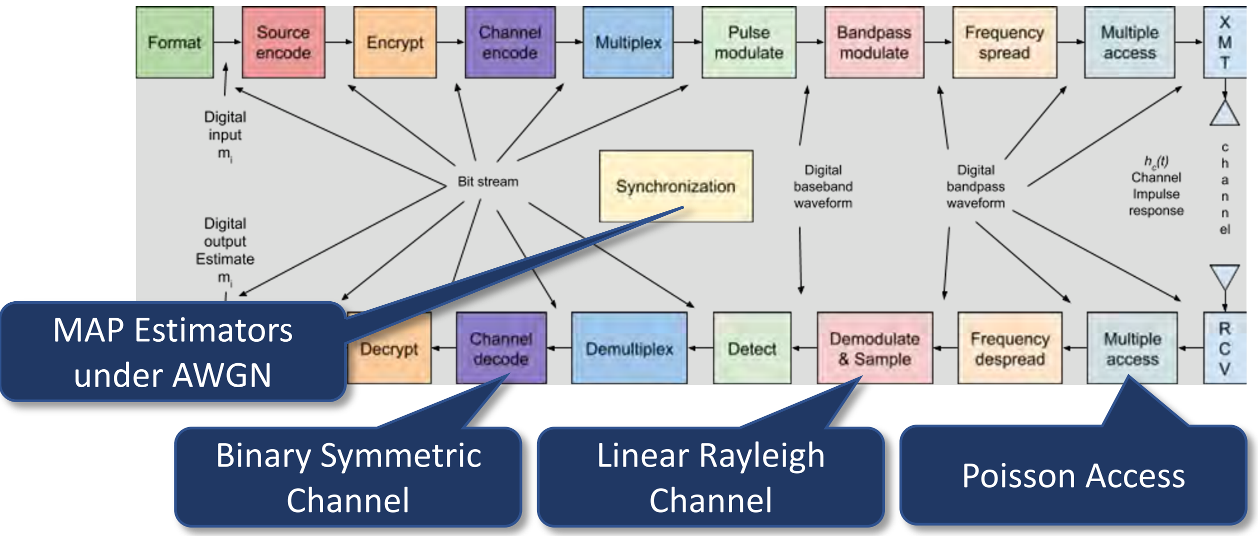
- Device count accelerating
  - Carriers looking beyond people for growth
  - Devices, applications and services
  - Factories, Infrastructure, Vehicles
  - 2020: 20-30 Billion devices
  - 2025: 75 Billion devices
  - 2030: 15+ devices per-person
- Fundamentally Requires better multi-user capacity & Spectrum sharing
  - Efficient spectrum and power consumption
  - Varied QoS and service requirements
  - Complex dense sharing requirements
  - Utilization of difficult new bands
- Rapid growth in demand on wireless
  - Demand for better algorithm to understand, utilize, and share spectrum across all of this.

Data Driven Methods Changing the Design Approach

Communications Engineering Approach Today

- Complexity creates difficult design & optimization problems
- **Tools for optimizing systems have not scaled with complexity.**
- Systems today designed & optimized by component on statistical models
  - Often precludes joint / end-to-end optimization
  - Simplified statistical world models for each module
  - Both miss opportunities for performance





- **Machine Learning Communications Systems**
  - End-to-end optimization ... Using real world measurement instead of simple models
  - Captures additional effects and information in real world data and algorithms
  - Results in energy efficient concurrent models

The Problem: RF Channels in Complex & Dense Environments

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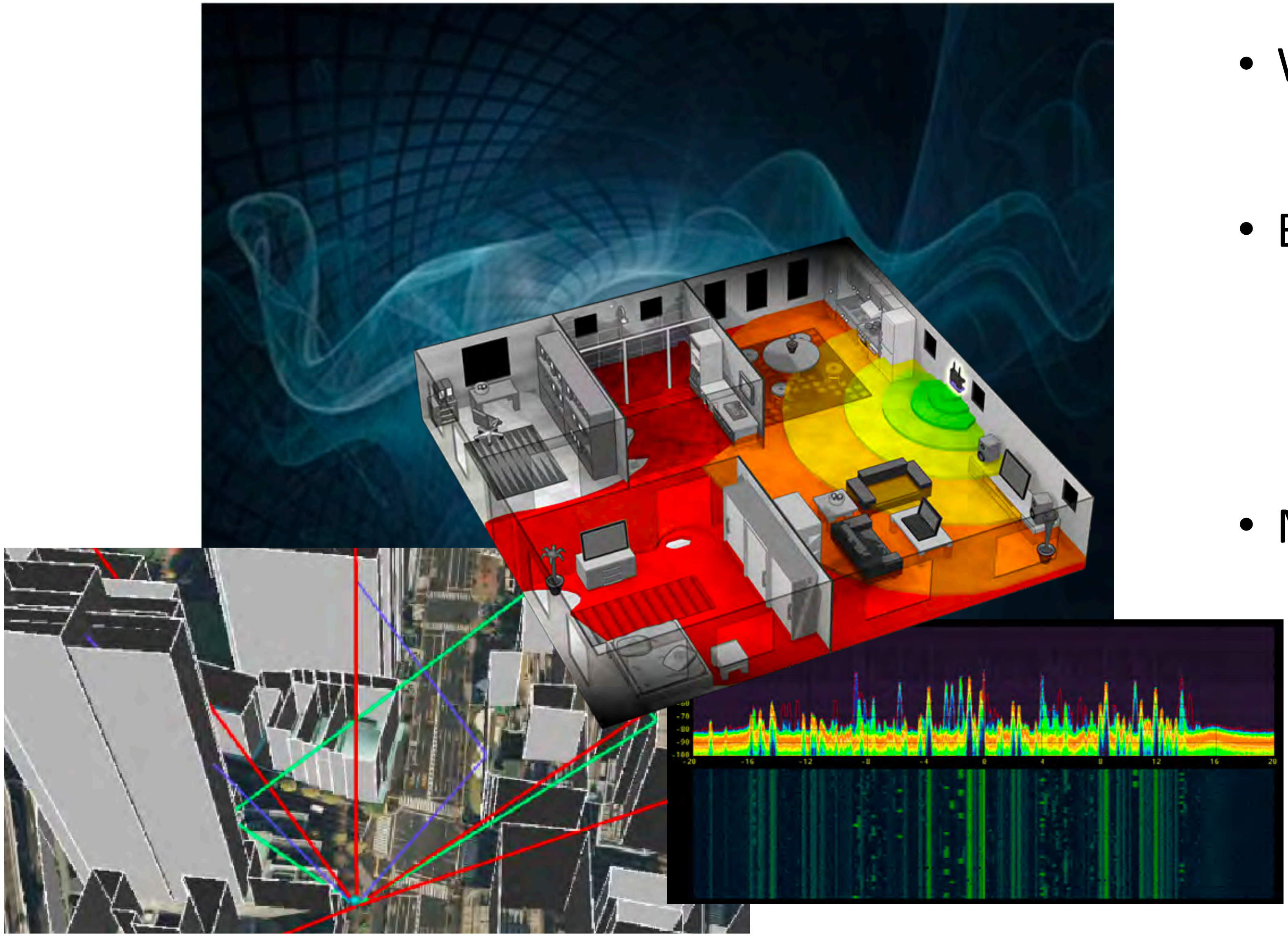


- We have strong Physics models
  - Maxwell's equations / Snell's law
  - Ray tracing & precise EM prop. modeling
- But do we really know parameters
  - Exact geometries & surface properties
  - Hardware & near-field effects
  - Numerous interference sources
  - Prop. mediums & environmental effects
  - Coupling non-idealized antenna patterns
- Modeling all of this is intractable
  - Becomes a data problem simply capturing the geometry, propagation effects, etc.
  - No way to escape complexity of data
  - Systems we're optimizing today are dense multi-user systems in these environments where we can't ignore these contributions!

Fundamental Challenges in Wireless

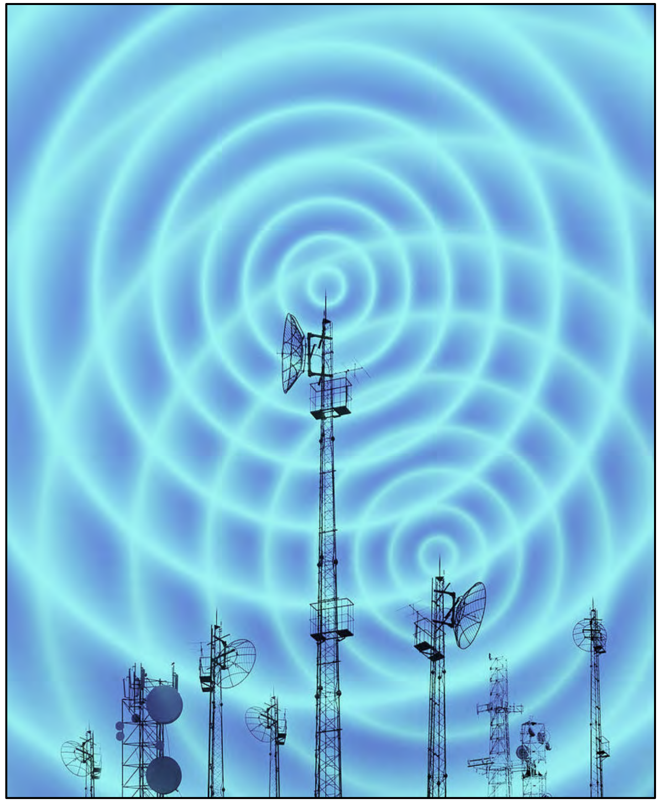
Leveraging data-driven DL approaches to core wireless problems

Spectrum Sensing & Awareness (OmniSIG)

Rapidly identify Devices, Threats, Interference, Use

Improve Radio Access Performance (OmniPHY)

Improve MU Efficiency, Power Efficiency, Experience



End-to-end Learning of Better Comms Systems

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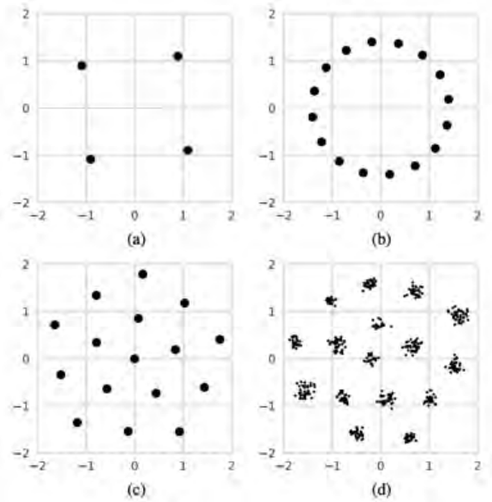
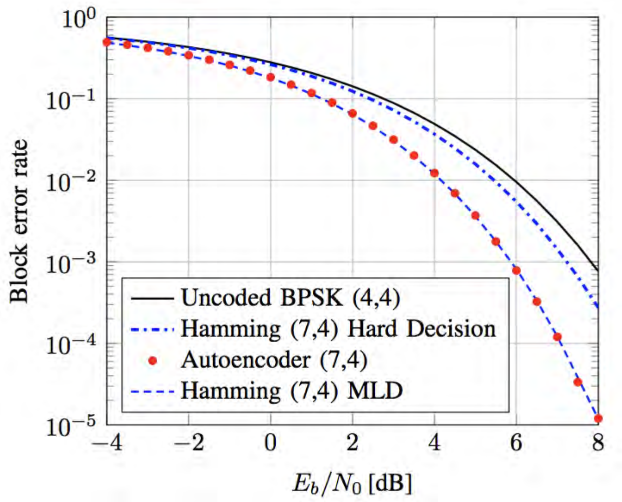
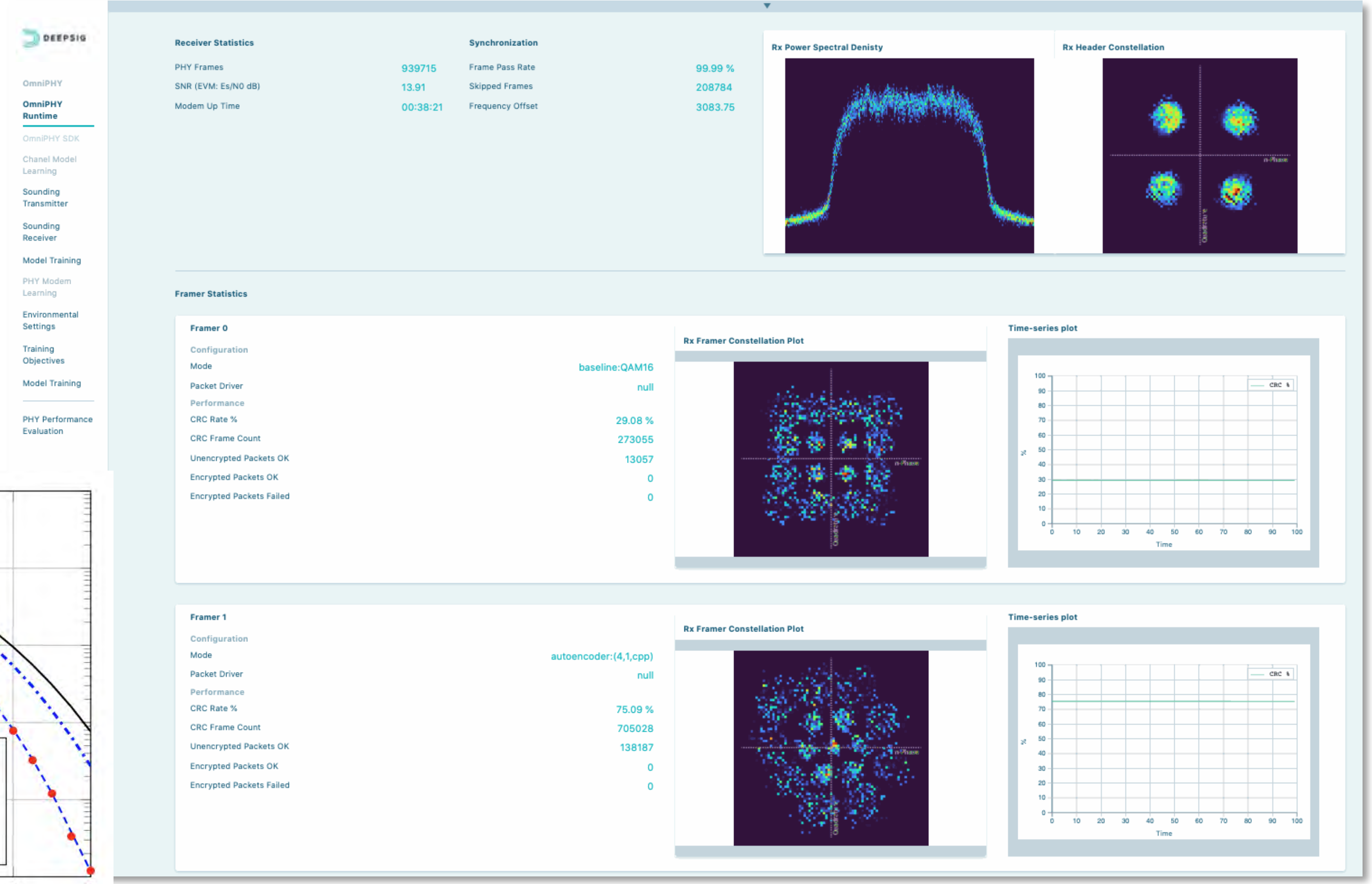
Learning driven encoding schemes are effective – and can outperform many conventional models

- Cast the communications problem as a ML problem to learn how to encoder and decoder for a given channel.
- Autoencoder variations are state of the art for many compression problems – good at information representation
- Learning both ends of a communications link can lead to a much more resilient, higher performing communications link!
- Examples below show we can
    - Learn some degree of error correction capacity at multiple rates
    - Learn better solutions over the air under variety of impairments





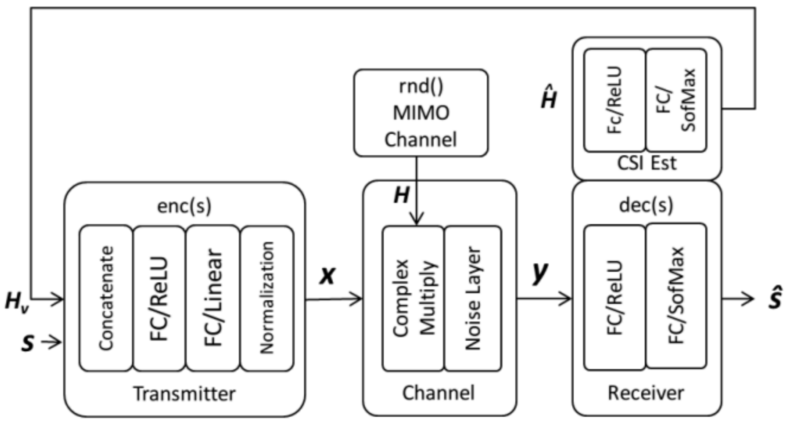


OmniPHY Runtime Engineering UI

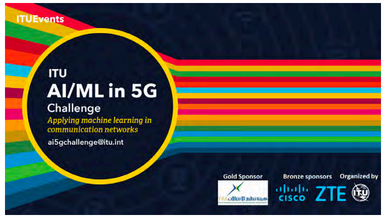
What Constitutes End-to-End?

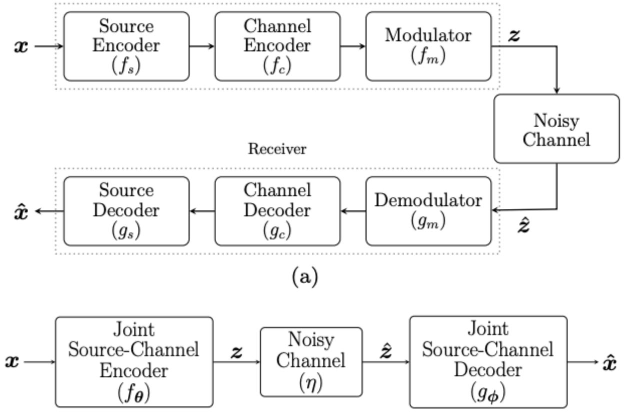
Numerous ways to think about communications systems

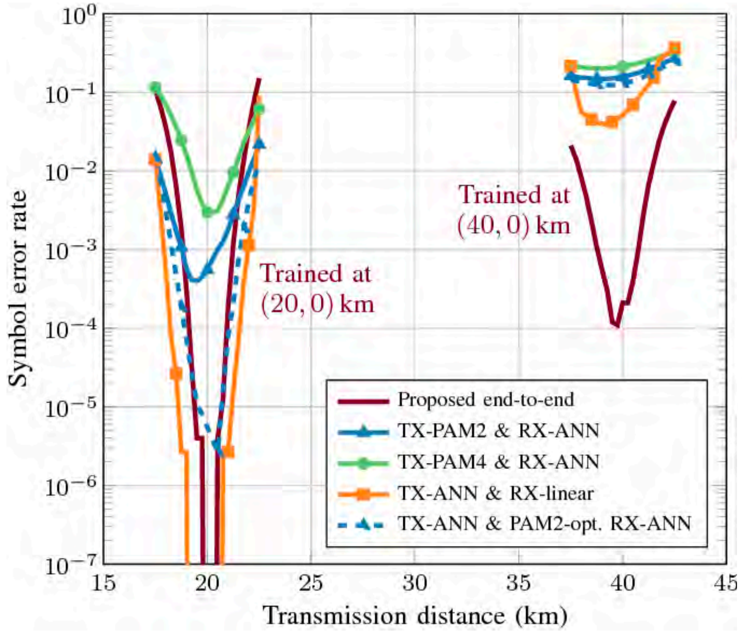
- Online Adaptation & Updates between UE/BTS
- End-to-end over MIMO Configurations
- End-to-end including Source Coding
- Multi-user schemes
- Learning for quantization
- Learning for CSI feedback
- Learning for frame & pilot design
- Optical systems, etc



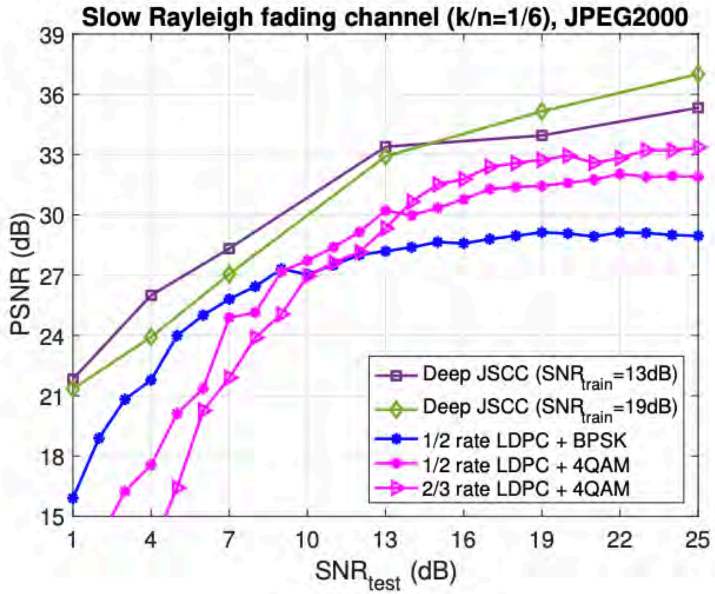
MLC ETI: Resources & Datasets







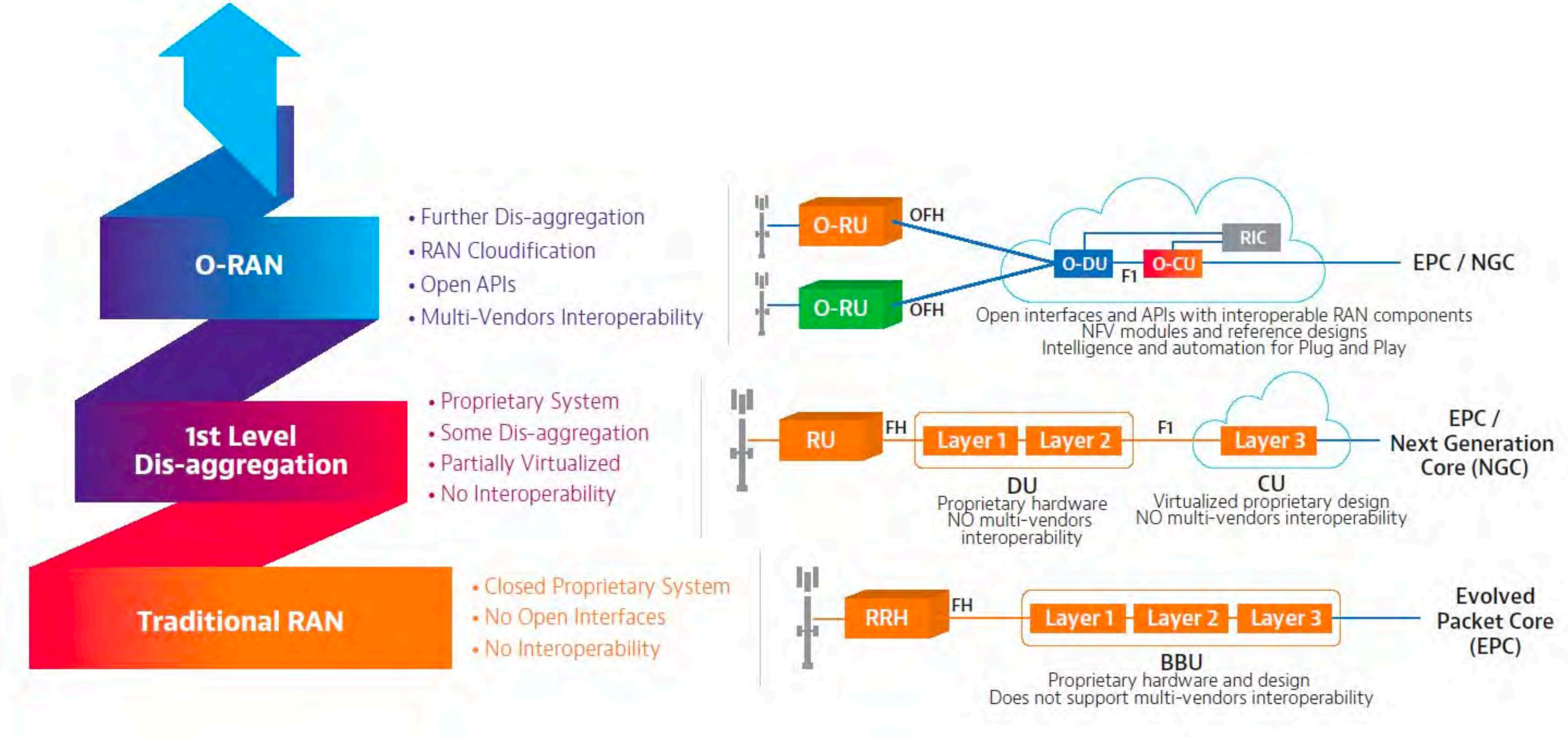
End-to-End Deep Learning of Optical Fiber Communications, Karanov et al



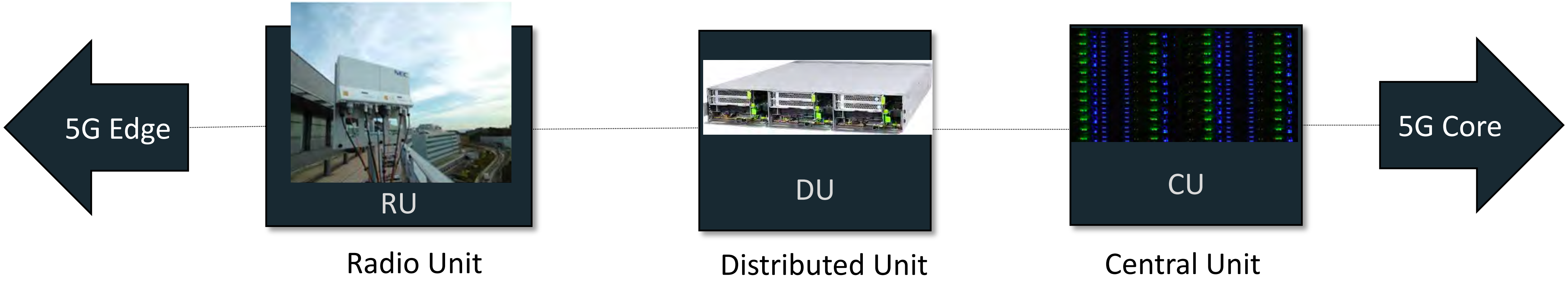
Deep Joint Source-Channel Coding for Wireless Image Transmission, Bourtsoulatze et al

Rapid Growth of the Open RAN / vRAN Ecosystem

Open RAN is splitting up the cellular hardware and base-station hardware and software ecosystem



Open RAN Opening Components up for Enhancement



- Open RAN is making components, data, and algorithms within vRAN more accessible
  - Allows algorithm innovation within commercial 5G stacks
  - Significant optimization without needing to build a whole stack or one large vendor
  - OpenRAN needs this algorithm and performance innovation to compete with Tier 1 vendors
- Numerous Machine Learning & AI Opportunities within all of these
  - Our focus has been heavily within the DU in the 5G NR L1
  - However L2, L3 Optimizations in scheduling, resource management, and tightly coupled applications – numerous opportunities
    - Many of these are the main R&D focus for integrators and operators today

Over-the-Air 5G gNB Receiver Learning

- Learning better performance in local channel
  - Learning to better cope with local conditions
  - Learning to suppress local interference better
- Over the air demonstration of gNB Rx learning
  - Better metrics than expected from simulation
  - Exploiting structure and non-whitened distributions
  - Especially robust interference from other emitters
  - Often 4-5 dB better EVM during interference events
- Compatible with todays standards unchanged
  - Numerous methods can be used transparently
  - We can leverage ML/AI today in 4G/5G vRAN
  - Even more possibilities longer term in evolution
  - (This is where Beyond 5G and 6G become interesting)
- Measurement-Data in the loop is critical
  - Simulation is not sufficient for algorithm R&D
  - Statistical models often insufficient

Validating Learning on the Multi-User PUSCH Channel

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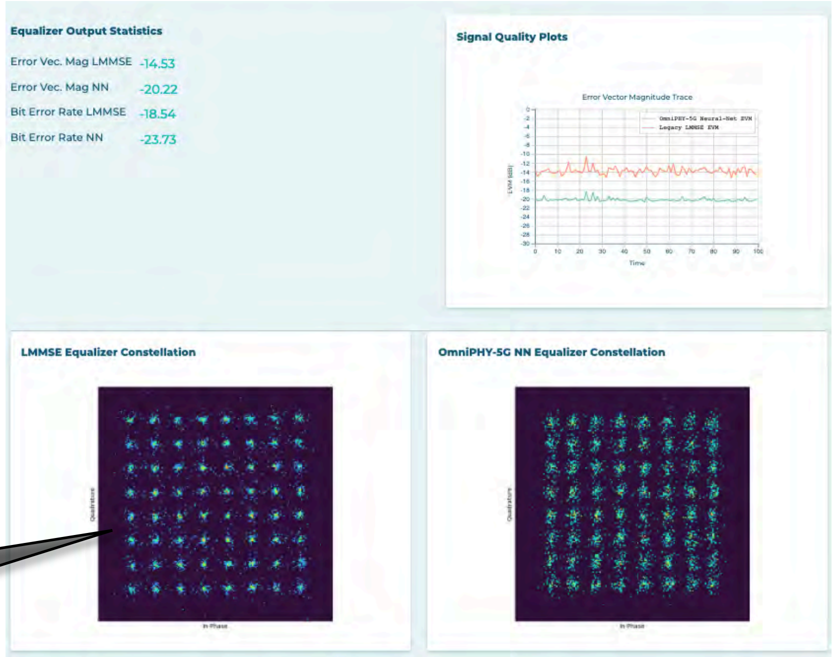
Scaling to Multi-User, Multi-Antenna, and Multi-Channel

- Multi-User TDD Learning Demonstration
  - Separate CSI per-user will learned base UL L1 converge effectively?
  - Demonstrates scaling effectively in MU TDD 5G-NR system over the air
  - Need to scale to 100’s of UE’s and Massive MIMO scale TRX in practice
- OpenRAN allows us to scale/validate /w commercial equipment

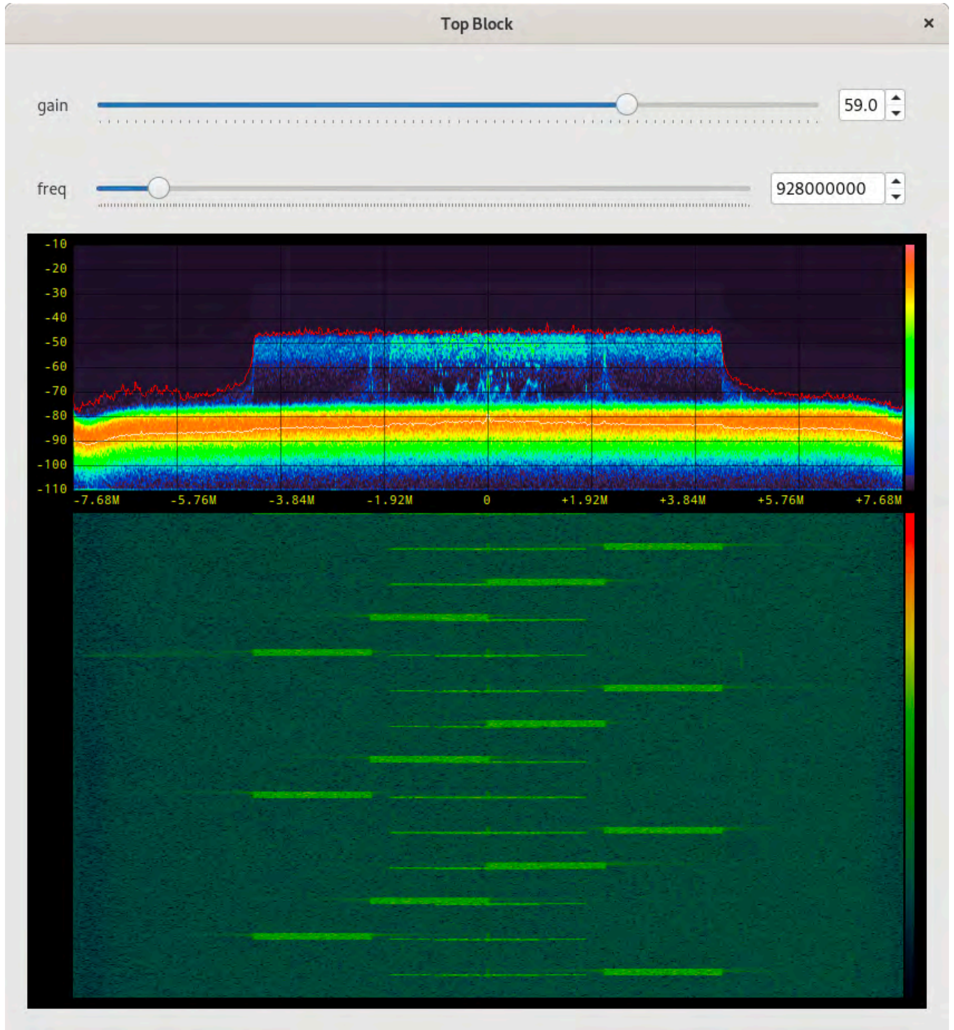
6dB EVM Reduction

5dB BER Reduction

Multi-User QAM64 & QAM256 Monitoring



OmniPHY-5G Engineering UI



Validating Learning under Harsh 3GPP TDL Models

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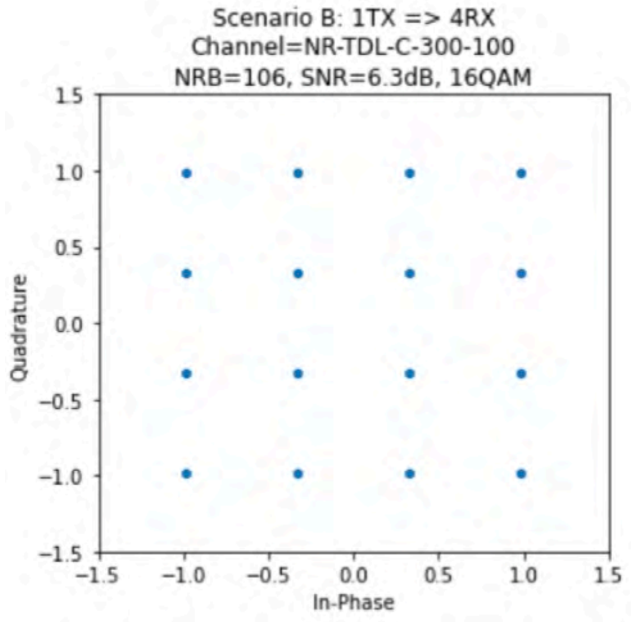
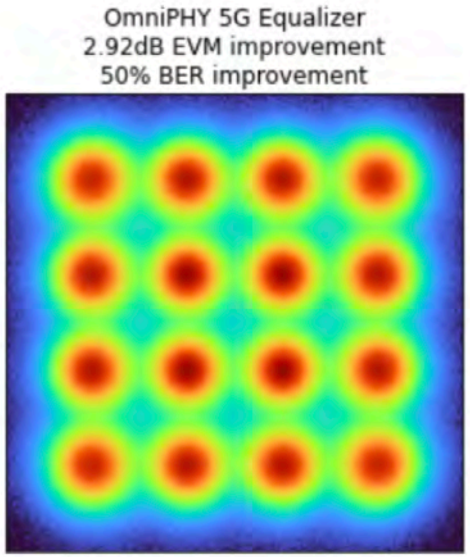
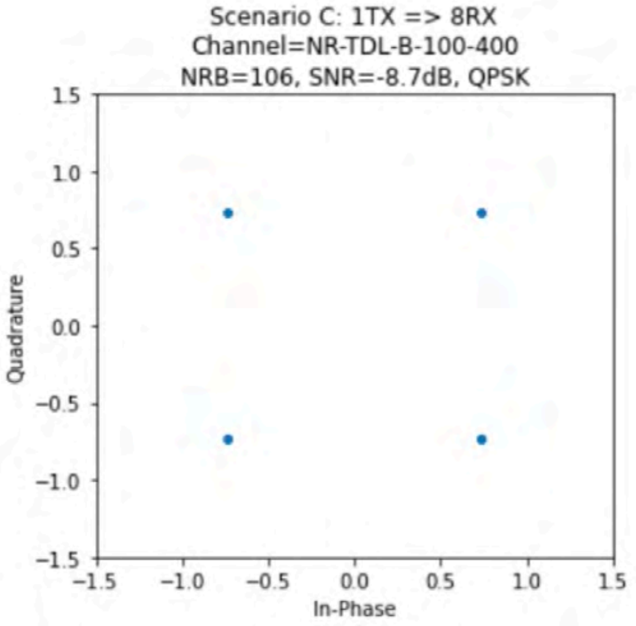
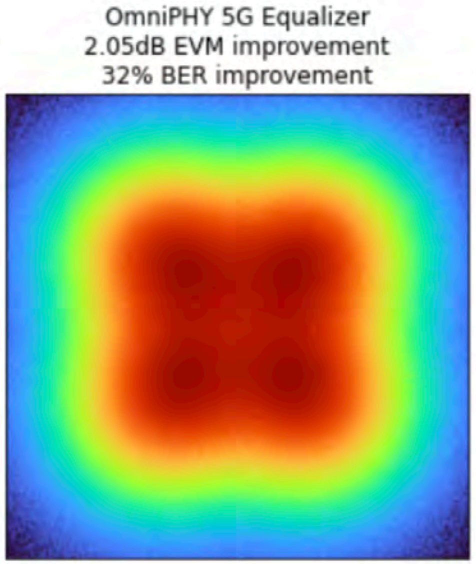
Performance Comparison pervasive MMSE + Weiner Filtering Method with Harsh TDL Fading Models

- Rigorous carrier-grade 3GPP channel model and FRC mode tests
- Can Significantly improved EVM and BER metrics in all cases we've tested
- Inference execution latency critical - can outperform traditional MMSE / SVM based methods
- Learned estimation, combining, and equalization of 1x4 and 1x8 MIMO configurations shown
- Approach scales to Massive MIMO configurations with even more performance benefits
- Can be accomplished with very small models (<10k params, faster than conventional algorithm)









Spectrum is Rapidly Becoming More Dynamic

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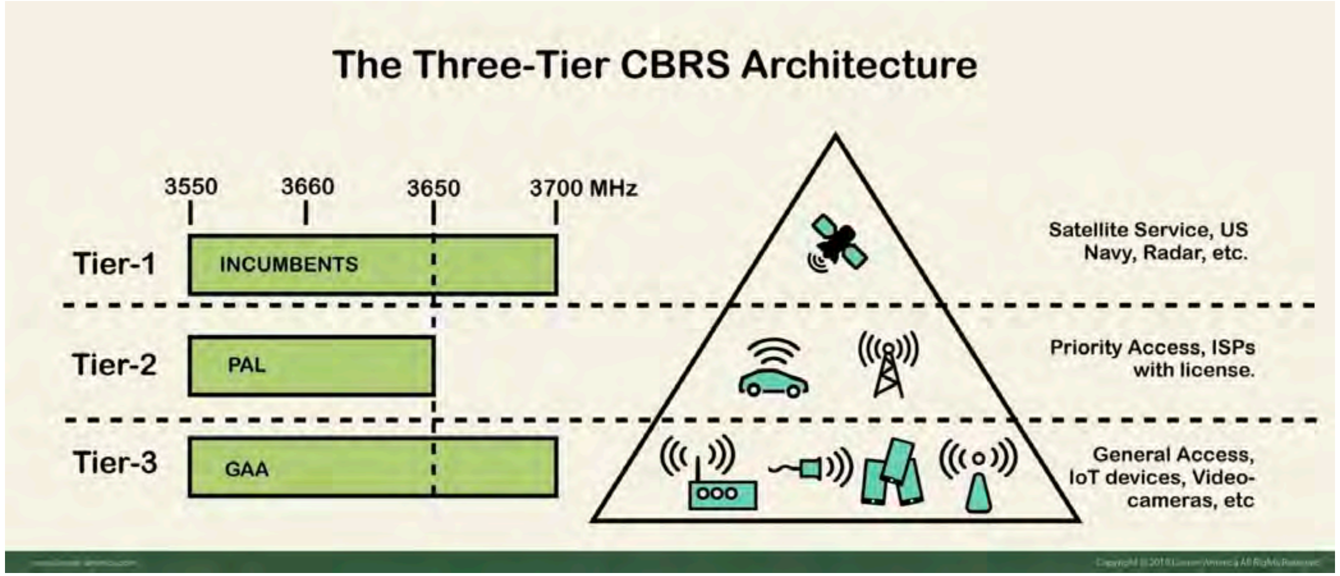
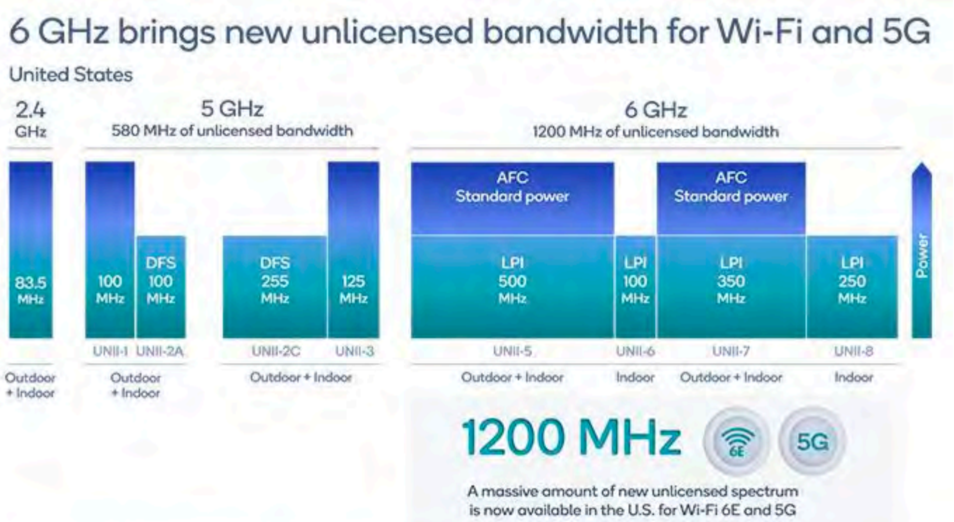
Spectrum Sharing emerging and becoming reality in many bands

- CBRS, 6GHz, and other Shared Bands becoming much more dynamic!
- Initial CBRS secondary users must register with a database –
  - Propagation models are generally simplistic and not accurate in urban deployments
  - Can not achieve high density efficient deployment without sensing
- 6GHz band expected deployments for LTE-U, NR-U, and WiFi 6E / 7
  - Important for wireless nodes to be able to sense and react to the spectrum around them –
  - Recognize what is operating in nearby spectrum, what they might interfere with, and where dense re-use is possible
- RAN awareness of band occupancy and propagation/interference is a critical enabler



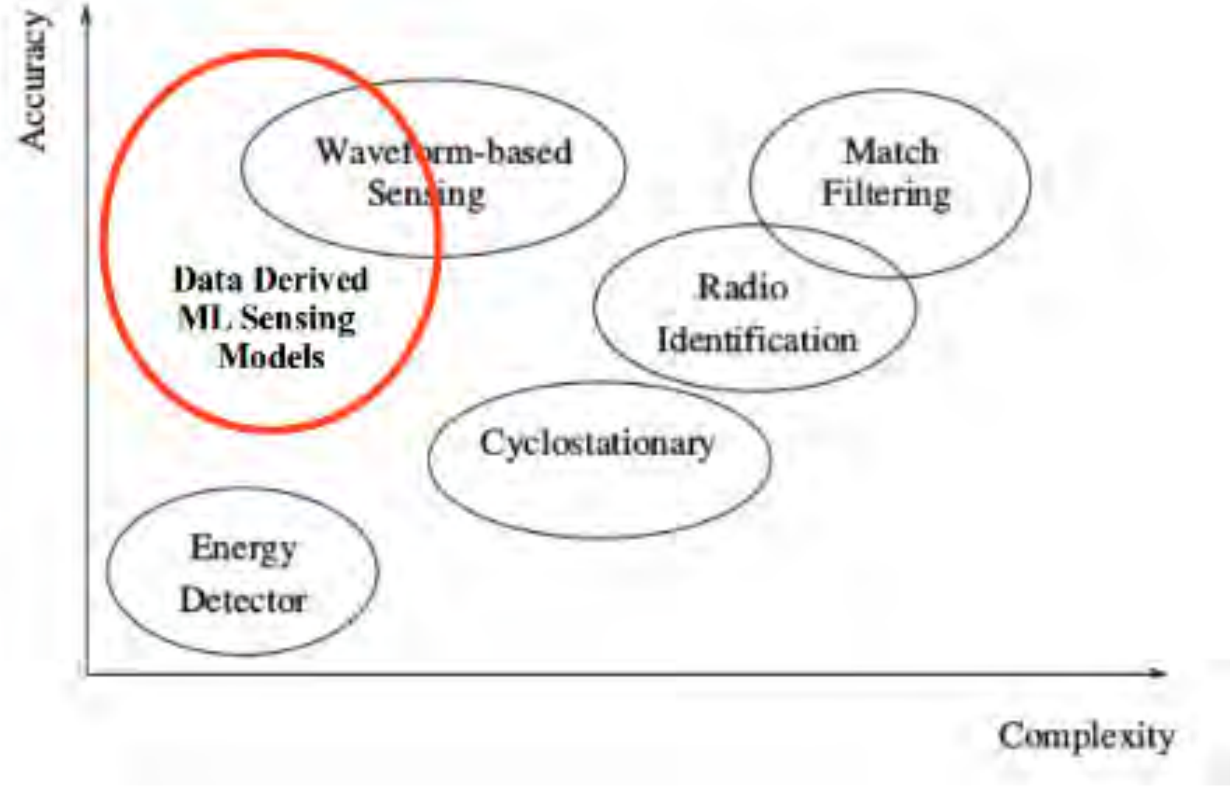


Source: Qualcomm news release

AFC= Automated frequency control, DFS= Dynamic Frequency Selection, LPI= Low power indoor

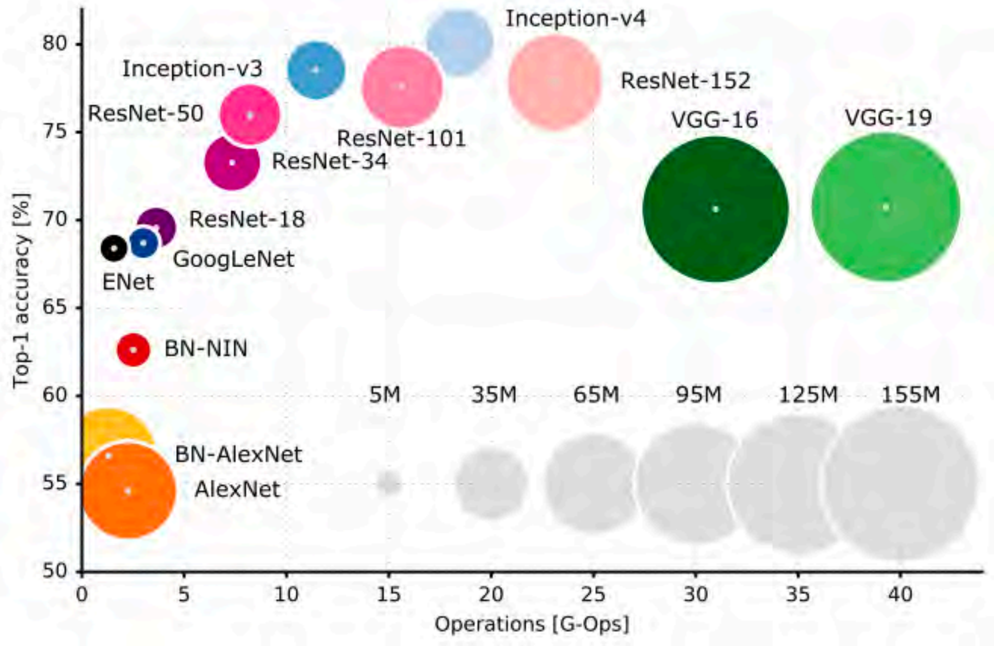
High Level Spectrum Sensing Tradeoffs

General Sensing Approach Performance



- Traditional approaches to sensing have suffered from complexity, brittleness, over-specialization
- Deep Learning architectures continuing to move in the right direction
- Practical sensing is finally accurate & feasible

Neural Network Architecture Evolution



Single Signal Classifier Performance

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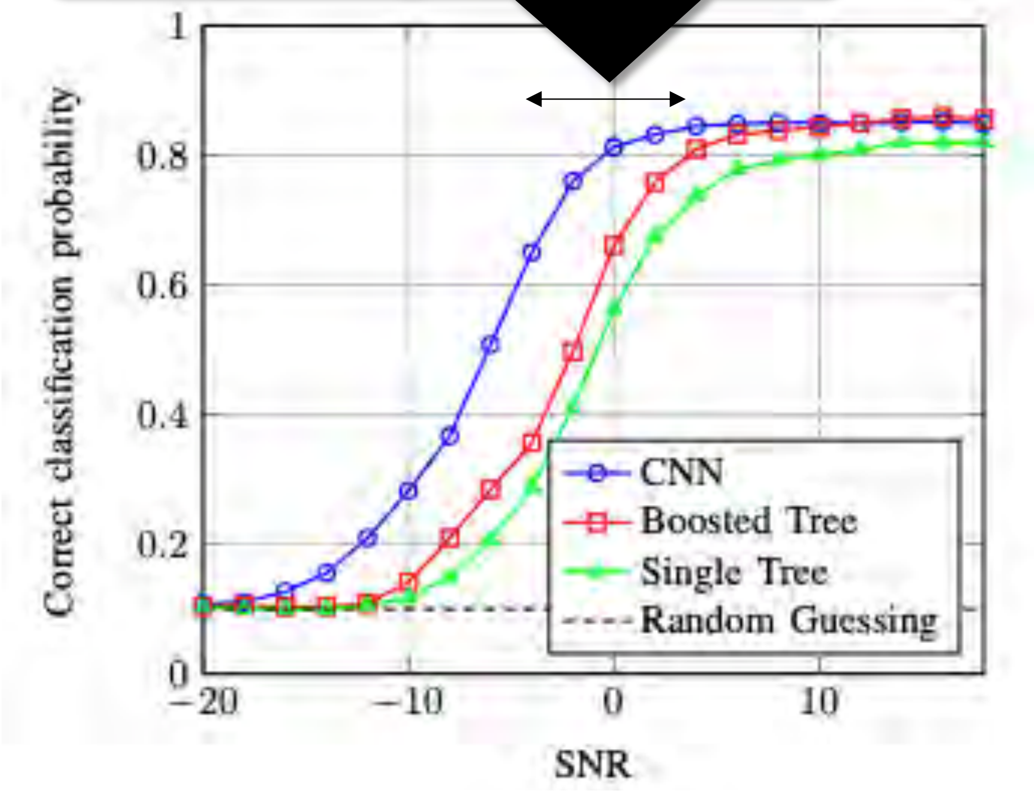
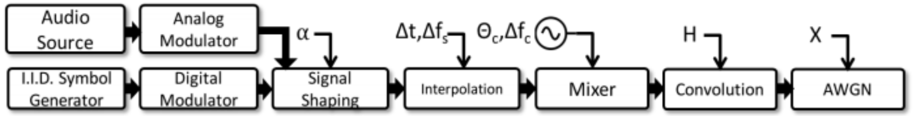
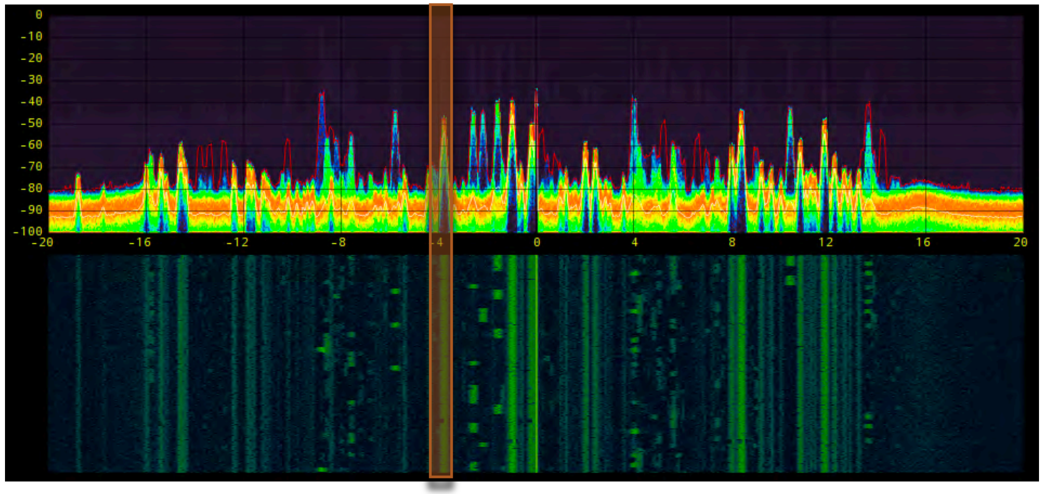
Typical 6+ dB Performance Advantage
Often more under impairments

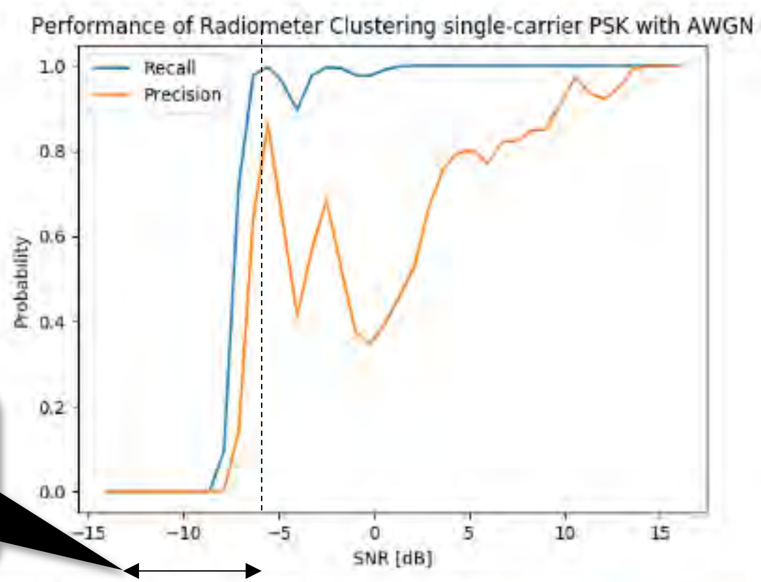




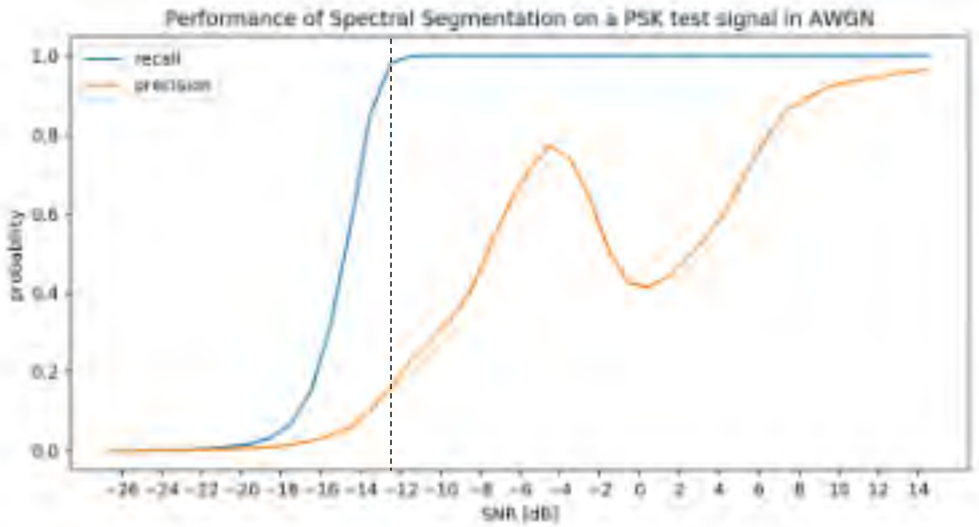
- Early work demonstrated
  - Even simple CNN's extremely effective at data-driven single signal classification
  - Significant advantages in computational complexity and accuracy/sensitivity
  - Numerous methods from DL / computer vision to make this work better
  - RF Domain knowledge is important
    - The data must match target distributions
    - Propagation and augmentation

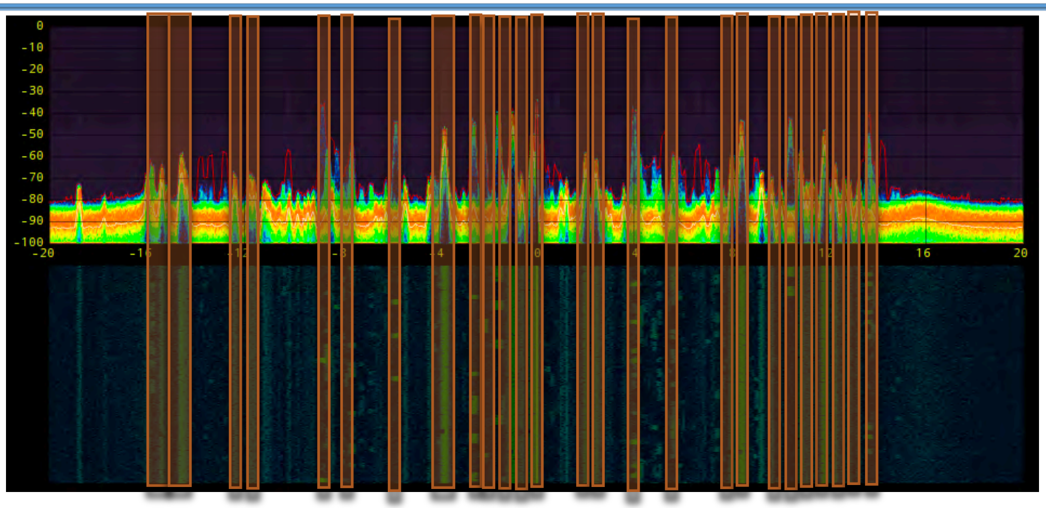


ML Driven Wideband Detection Performance



Significant Sensitivity Advantages

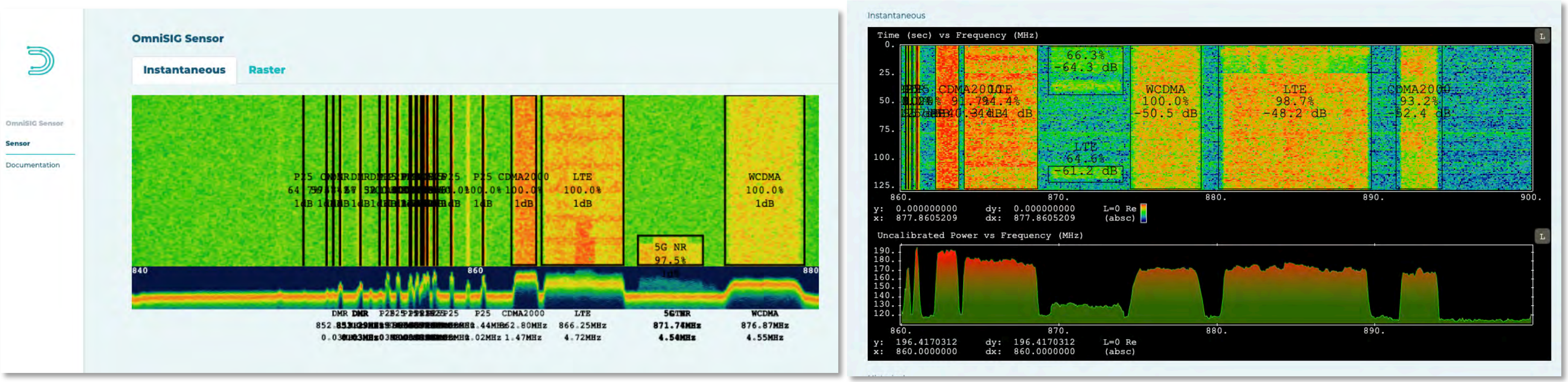




- Real world problem is often signal detection in complex wideband RF environments
  - DL architectures can tackle this problem as well
  - Significant advantages over traditional energy-based-methods (Radiometer, etc.)
- Precision/Recall curves demonstrate significant sensitivity advantages
  - Even under “worst case” AWGN
  - *Recent Work from (West. et al)*

Sensing: Putting it all Together

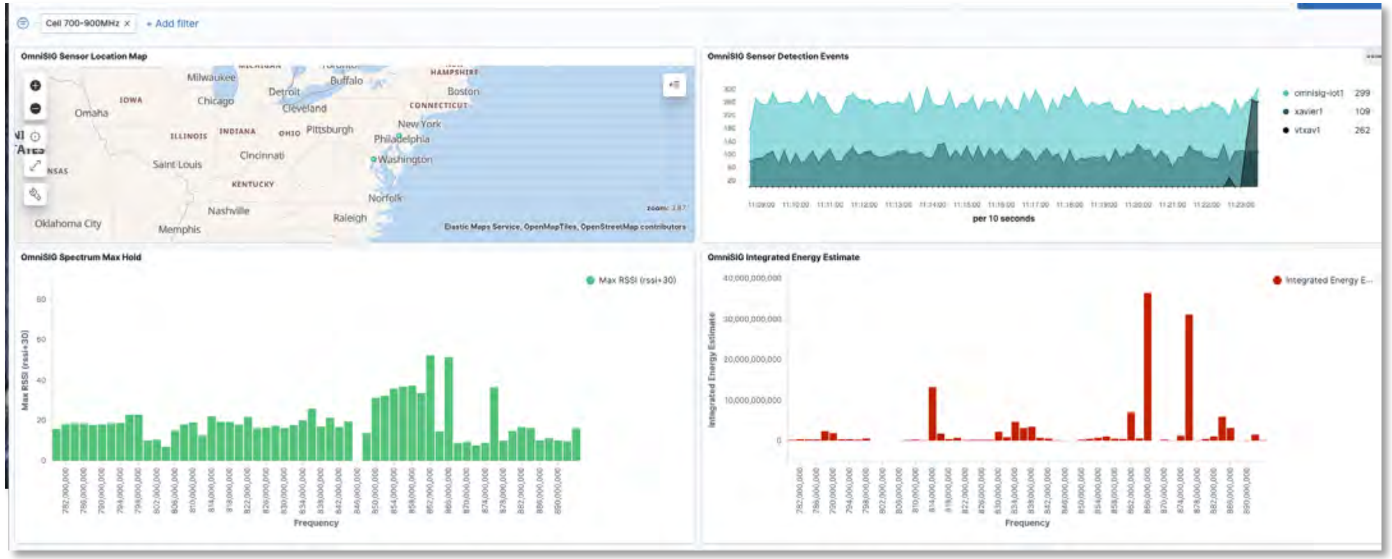
- Rapid Detection and Classification
- Can now reach excellent precision/recall performance on very short observations & in complex congested RF environments
- Rapid single burst detection and awareness of radio access & behaviors
- Next generation of RF Spectrum monitoring, access, sharing, security now has compact high-level information to make decisions on in real time



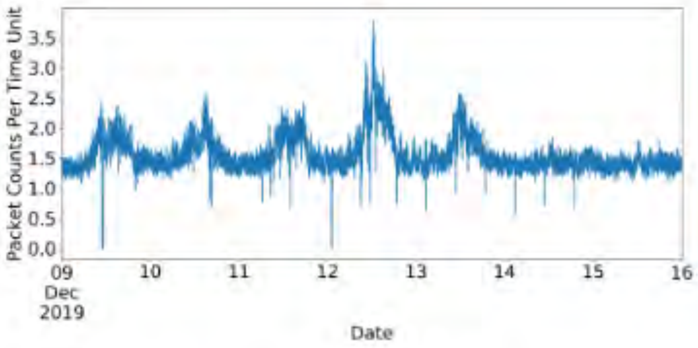
OmniSIG Sensor Engineering UI

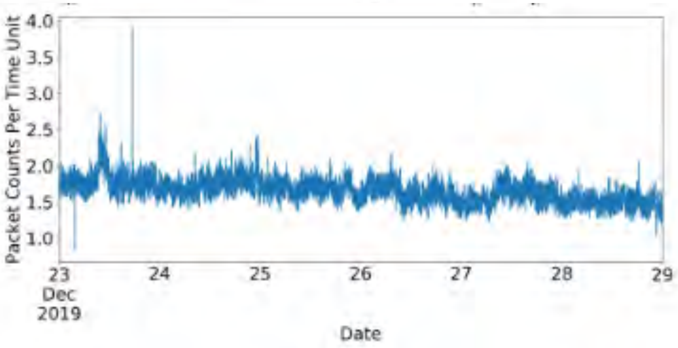
Sensing: Structured Data Analytics

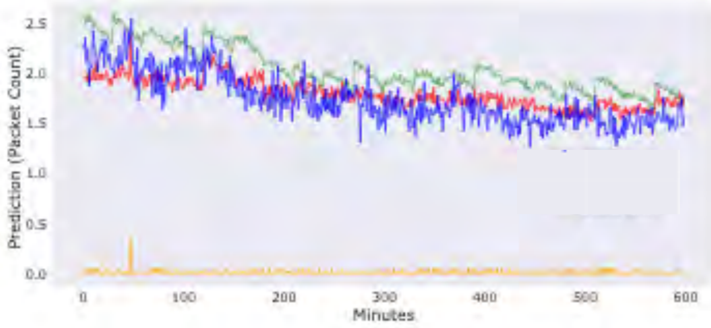
- Unleash existing analytics tools on wireless problem
  - Time-series forecasting and prediction
  - Mature SIEM and monitoring tools
  - Change and anomaly detection across whole spectrum
- Work-week vs Holiday week wireless activity
  - Increasingly performance predictive & A.D. models



OmniSIG Analytics Dashboard



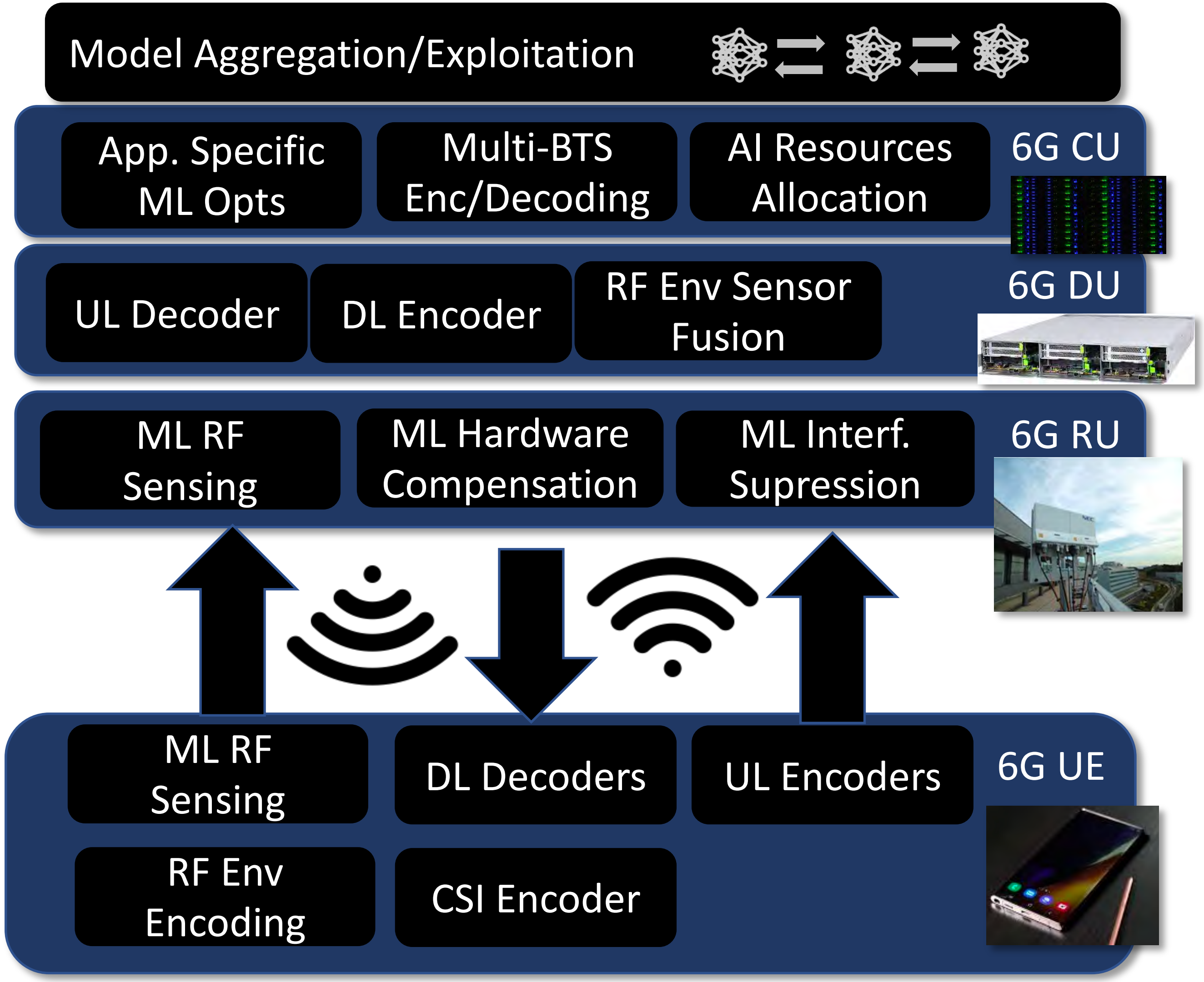




Where is this Going …. AI/ML in Beyond5G/6G

The 6G PHY Will be Data-Driven End-to-End

- 6G PHY will need to achieve
  - Order of magnitude more efficient processing
  - Order of magnitude higher content rates
  - Order of magnitude more efficient spatial use
  - Many Billions of Devices & 1+ Tbit rates
- Channel Encoding is the Beginning of the Problem
  - CSI Encoding, Feedback Learning, Pilot Learning
  - Dynamics Conditioned Learning
  - Smart Location Aware Algorithms
  - Rich Online Feedback Information Flows
- Ultra Massive MIMO & Spatial Exploitation
  - Smart Surfaces and built in antenna strips
  - Hundreds or thousands of elements to exploit
  - Degrees of spatial re-use we've never seen today
  - Blurring between Sectors and Spatial Modes
- Spectrum Awareness, Application Awareness
  - Ultra-Small and Low-Power IoT Devices
  - Enabling better compensation and suppression
  - Better end-application performance
- Enabled only by the intricate distributions of cell geometry, user behavior, and exploitation of data.



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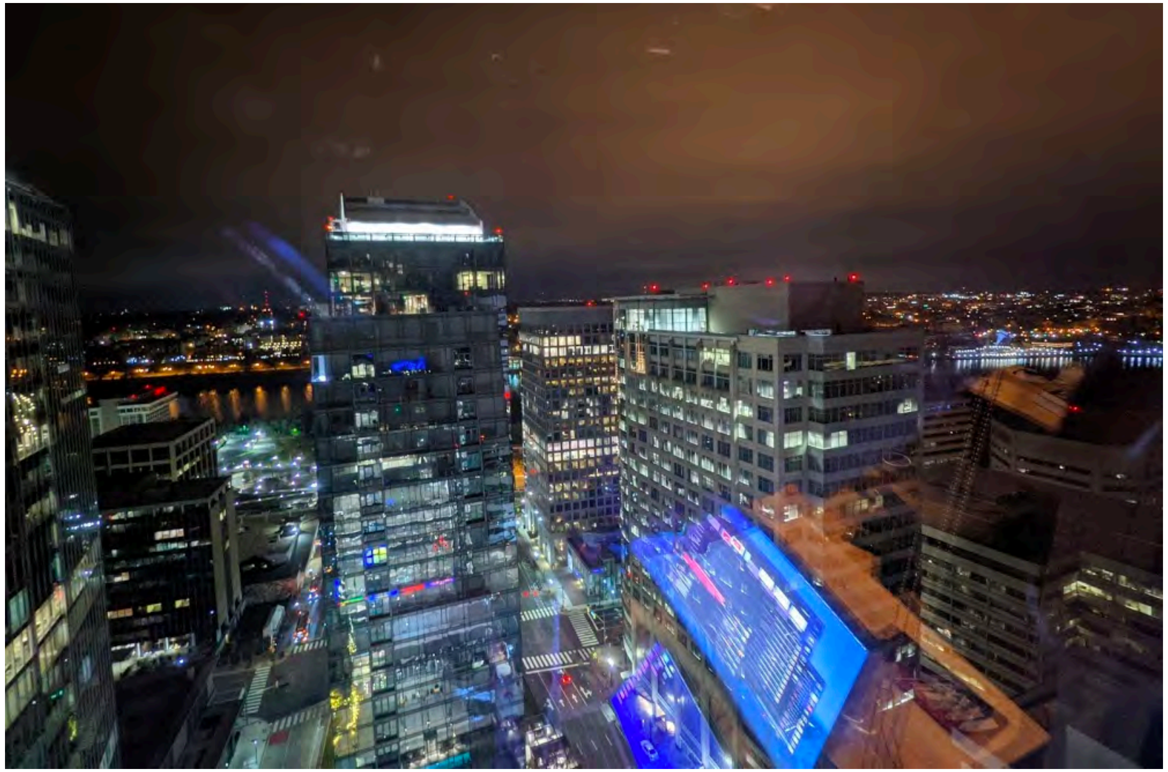

- DeepSig 5G Open RAN and Sensing Efforts Growing Rapidly in this area!
  - We're looking for more vRAN and OpenRAN trial partners, and hiring!

- Questions? info@deepsig.ai