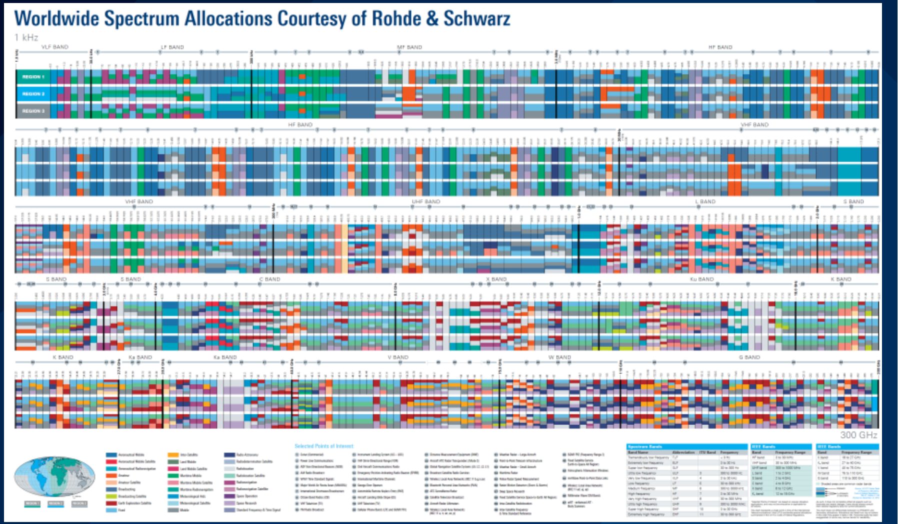
TESTING FOR COEXISTENCE IN CROWDED AND CONTESTED RF ENVIRONMENTS



Tim Fountain
Market Segment Manager, RADAR & EW

All information was acquired from public domain sources

ROHDE&SCHWARZ

Make ideas real

AGENDA

- Coexistence in Contested, Congested, Cooperative & Cognitive RF environments
- Coexistence Examples
- Technologies & Techniques for Coexistence Scenario Testing

COEXISTENCE IN THE RF SPECTRUM

- As the demand for RF spectrum access, we are moving from a fixed spectrum allocation model to re-allocating, sharing and dynamically allocating spectrum
- Typically, this sharing is cooperative, but sometimes it is in a contested environment where actors are attempting to jam or block communications
- Congestion happens when multiple users or devices are trying to access the same portion of spectrum
- Cognitive Artificial Intelligence/Machine Learning (AI/ML) algorithms can be used to implement strategies for spectrum sharing
- The key to efficient use of the spectrum is realistic Over The Air (ATA) testing of functional performance of planned usage scenarios before:
  - Developing rules for how the spectrum is to be shared
  - Auctioning or selling spectrum

NOT A NEW PROBLEM

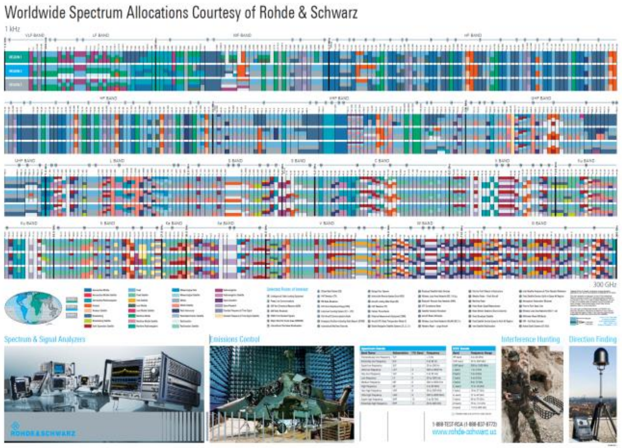
- Coexistence testing has been a cornerstone of many regulatory policies
  - FDA-2006-DD-003 RF in medical devices
  - FCC Class A, B, C EMI/EMC
  - MIL-STD-461 & MIL-STD-464
  - TEMPEST for USN shipboard systems
  - OHSA 29 CFR 1910 – control of RF and microwave radiation
  - EU Radio Equipment Directive (RED) 2014/53/EU
    - 1st time receiver performance was mandated
  - EU EMC Directive 2014/30/EU
  - …..
- However, an emerging issue is contention, congestion and re-allocation of specific portions of traditionally statically allocated spectrum to newer applications

EXAMPLES OF DYNAMIC SPECTRUM SHARING STANDARDS

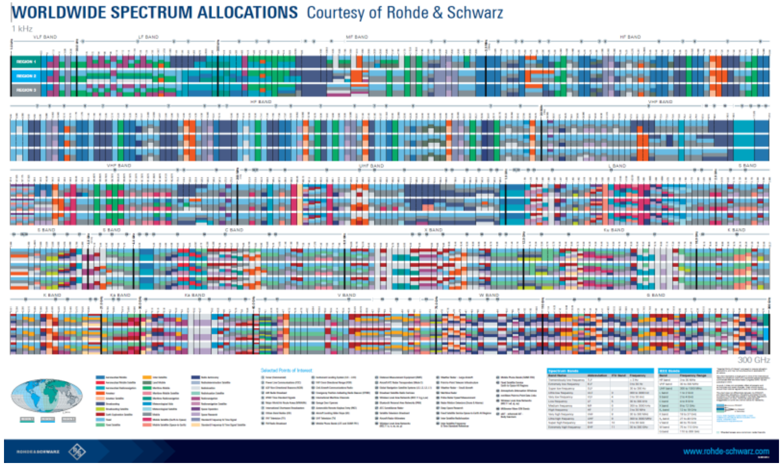
Radio Protocol	Purpose
DFS Dynamic Frequency Selection	WiFi devices and U-NII band infrastructure
DAA Detect and Avoid	IEEE802.15.4a – UWB communications in licensed bands (3-11 GHz)
AFH Adaptive Frequency Hopping	Bluetooth – improve robustness of radio performance in ISM band
DSS Dynamic Spectrum Sharing	Concerned with the operations of 4G/ 5G services. Migration enablement for shared carrier operation
SAS Spectrum Access System	Cloud based system for automated frequency coordination and priority access for the CRBS band ….in the US!

ITU RADIO REGULATIONS CHART 2012 VS. 2022

- WRC-12; WRC-15; WRC-19 – over 4,400 changes
  - (international) 3GPP Bands increase from 11 to 83
  - (regional) US 500MHz Broadband initiative (NTIA/FCC)

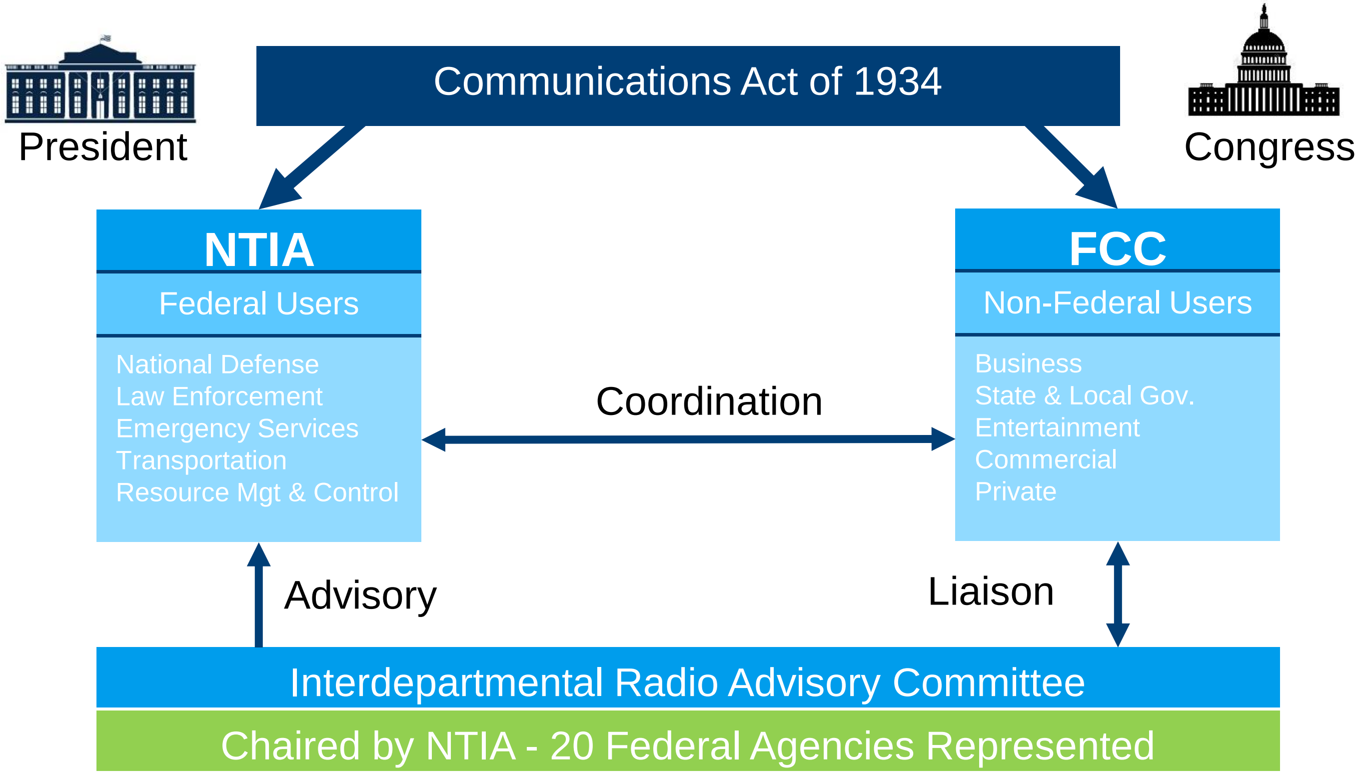


Source: 47 CFR 2.106
December 12, 2012 – based on WRC-12



ITU - Radio Regulations Articles Edition of 2020
Edition 2020 – based on WRC-19

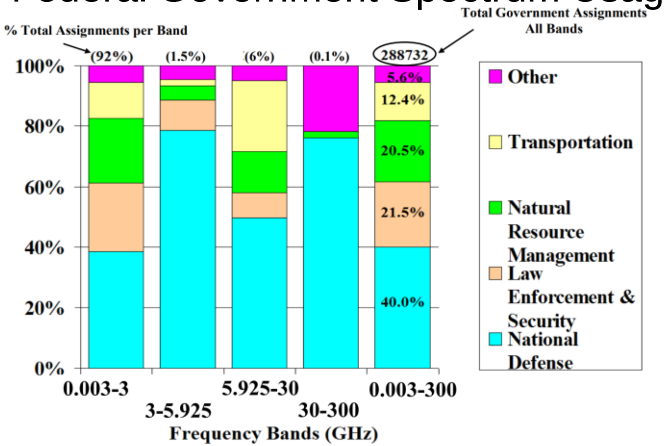
SPECTRUM REGULATION IN THE US



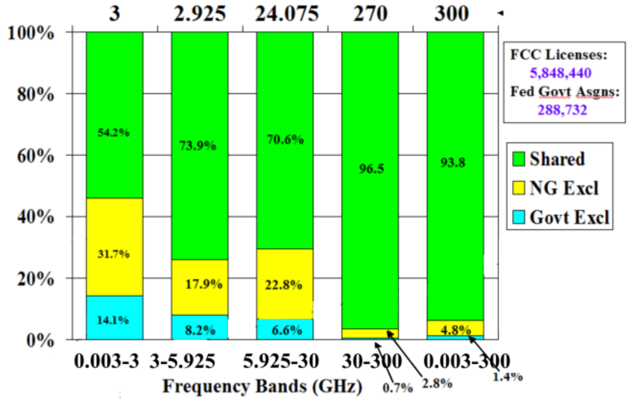
SPECTRUM ALLOCATION BY END-USER

- The most active and valuable part of the spectrum, due to propagation, is up to 3.1 GHz
  - The US government has about 92% of their operations in this band, with exclusive use of 14.1%
  - The private sector has exclusive use of 31.7%
  - Shared - **54.2%**

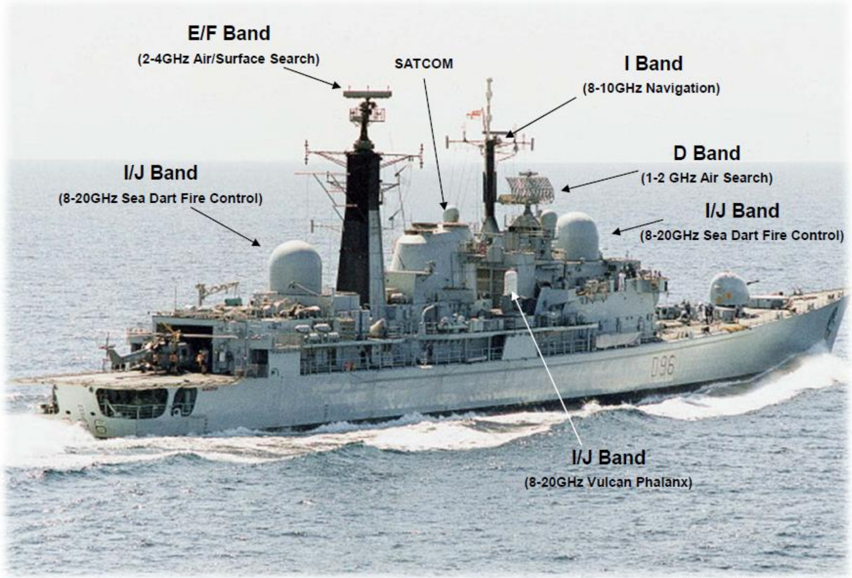
Federal Government Spectrum Usage



Spectrum Allocations



HOW DO WE BALANCE THESE COMPETING USERS?



BALANCING ECONOMIC & NATIONAL SECURITY

Growing Defense Requirements

- EW & Cyber Threats
- Realistic Test & Training
- Network & Communication Standardization
- Efficient EMSO Through Battle Management
- Constrained Access & Limited Maneuver
- Proliferation of Advanced Technologies



Growing Commercial Requirements

- WIFI
- 4G, 5G, 6G
- mmWave
- White Space Devices
- Connected Vehicles
- xIOT



Common Issues

Information & Mobility requirements
Weaponization of COTS Technologies
Non-traditional partners & adversaries
Global Proliferation of low-cost technologies
Sharing opportunities
RDT&E Investment

THINGS HAVE CHANGED

- DoD Challenges:
  - Test, train, exercise and operate both domestically and globally
  - Increasing demand for bandwidth
  - Increasingly complex sharing environment
  - Democratization of technology
  - Military geographic barriers eroding
  - Electro–Magnetic Spectrum Operations (EMSO) between US forces & partners
  - Requirement for resilient, agile & flexible systems
  - Operation across wider bandwidths to defeat threats
  - EW threats are more complex, cheap, commercially available, agile and frequency agnostic/hostile

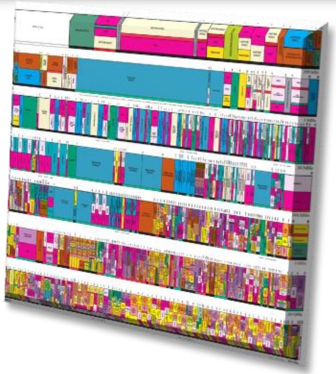
VISION

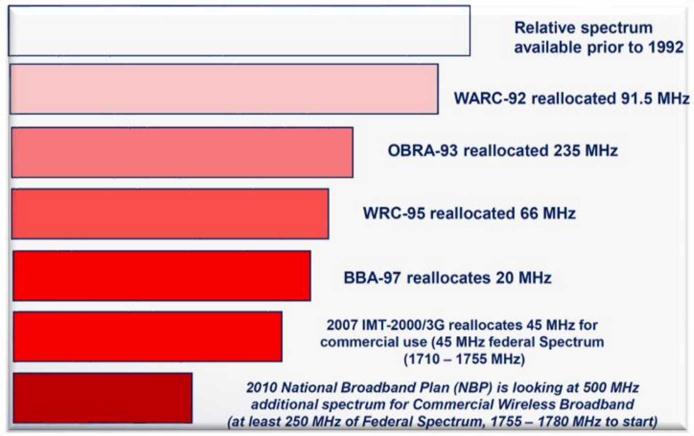
Current State

- Access when and where assigned
- Static & inflexible
- Exclusive
- Large Guard Bands
- Inefficient
- Limited Availability
- Manually Controlled

Future State

- Access when and wherever needed
- Dynamic Allocation
- Shared/Compression
- Agile
- Efficient
- Sufficient Supply
- Significantly Autonomous
- EMSO Aware





THE STAKES ARE HIGH….

- In the last 30 years ~100 auctions have raised **$230B** in revenue for the US treasury, as of spring 2022
- FCC Auction #107 - 280 MHz of mid-band spectrum in the 3.7 – 3.98 GHz band
  - **$81B** in licensing fees
  - 5,684 licenses awarded

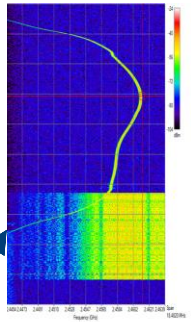
Bidder	Gross Winning Bids
Cellco Partnership (Verizon)	$45.45B
AT&T Spectrum Frontiers	$23.4B
T-Mobile License, LLC	$9.3B
United States Cellular Corporation	$1.3B
New Level II, L.P	$1.3B

Bidder	# of Licenses Awarded
Cellco Partnership (Verizon)	3,511
AT&T Spectrum Frontiers	1,624
United States Cellular Corporation	254
T-Mobile License, LLC	142
Canopy Spectrum, LLC	84

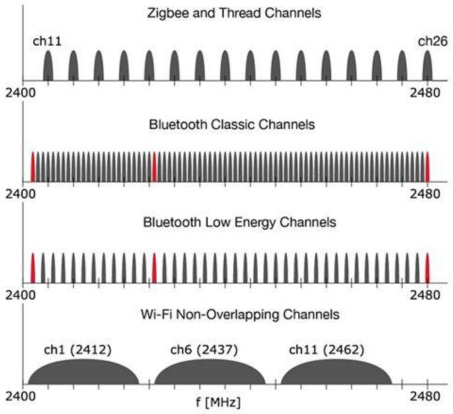
Congested	The unlicensed ISM 2.4 GHz band
Coexistence	Citizens Broadband Radio Service - CBRS
Contested	Airplane RADAR Altimeters and C-BAND 5G
Conflict	Ligado & GPS

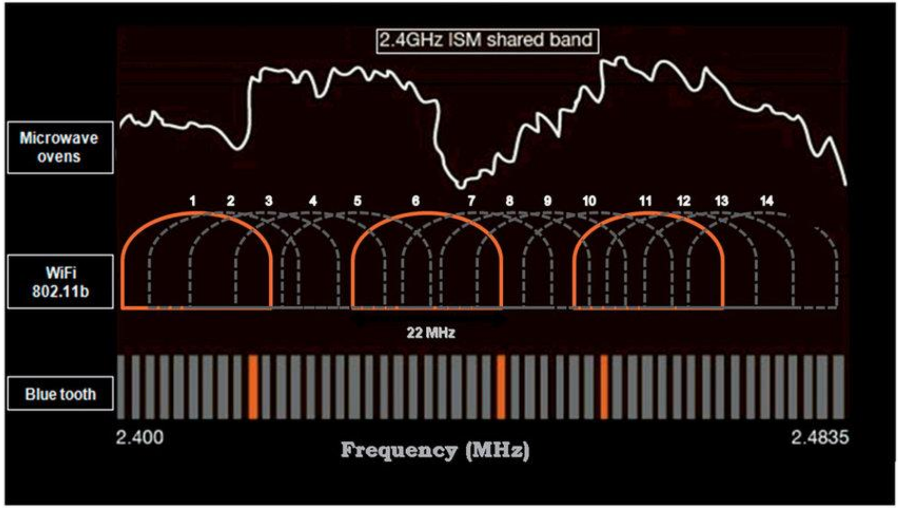
COEXISTENCE EXAMPLES

THE 2.4 GHZ BAND…



- ► Designated as the Industrial, Scientific & Medical (ISM) Band
- ► The classic coexistence example (some would say congested…)
  - – WIFI, Zigbee, Thread & Bluetooth, UAV control, Keyboard, Mice, RFID, NFC & Microwave ovens….
- ► 83.5 MHz of unlicensed bandwidth between 2.400 GHz & 2.4835





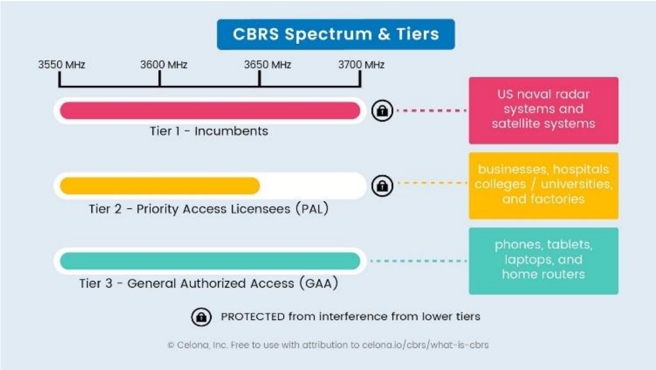
MANAGING CONTENTION IN THE ISM BAND

- Limiting Tx power
- Utilize more robust & efficient modulation techniques
- Spatial diversity with multiple antennas
- Directional antennas
- Divide spectrum into channels
  - However different protocols have conflicting channel plans
    - 802.11, WIFI, uses DSSS over 14 channels with 5 MHz spacing
    - 802.15.1, Bluetooth, uses FHSS over 79 1MHz channels with 1 MHz spacing
    - 802.15.4, Zigbee, uses DSSS over 16 channels with 5 MHz spacing
  - This leads to channel overlap and co-channel interference
- Frequency diversity, AKA channel hopping
- Contention detection & mitigation
- On-demand channel bonding and de-bonding
- Utilize other ISM bands (see table)

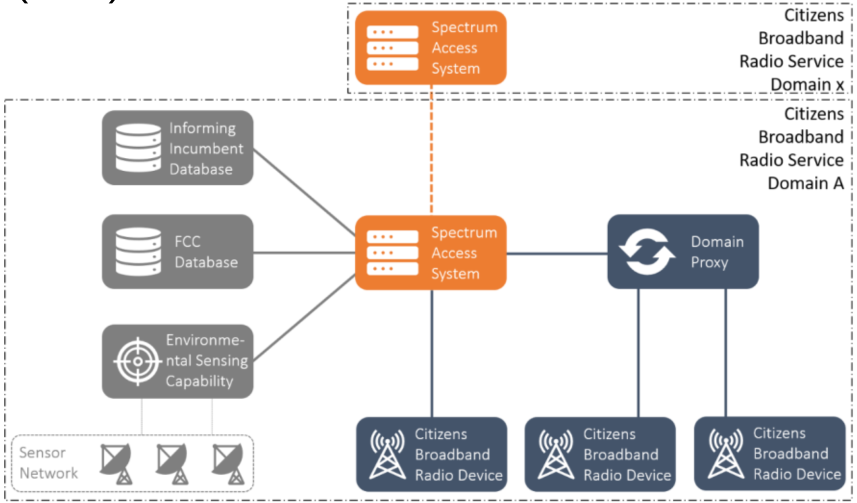
Frequency Range	Bandwidth
6.765 – 6.795 MHz	30 KHz
13.553 – 13.567 MHz	14 KHz
26.957 – 27.283 MHz	326 KHz
40.66 – 40.7 MHz	40 KHz
433.05 – 434.79 MHz	1.84 MHz
902 -928 MHz	26 MHz
2.4 – 2.4835 GHz	83.5 MHz
5.725 – 5.875 GHz	150 MHz
24 – 24.25 GHz	250 MHz
61 – 61.5 GHz	500 MHz
133 – 123 GHz	1 GHz
244 - 246 GHz	2 GHz

CITIZENS BROADBAND RADIO SERVICE (CBRS)

- CBRS operates in the licensed spectrum from 3.55 GHz – 3.7 GHz
- CBRS can be viewed as a mix of traditional licensed spectrum (LTE) and unlicensed spectrum such as WIFI
- Enables cooperative shared access between 3 tiers of users
- Access is manages by a Spectrum Access System (SAS) and sensors in the environment
- CBRS uses FDD with an LTE frame structure



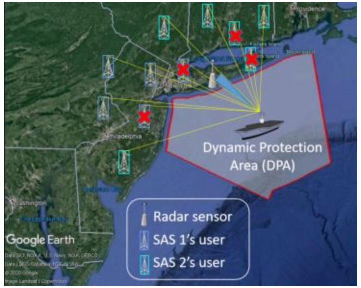
CBRS Tiers (Courtsey celona.io/cbrs/what-is-cbrs)



CBRS Control Architecture (Courtesy metaswitch)

CBRS TIER 1

- **Tier 1: The incumbents**
  - The incumbents have the highest priority in the CBRS system and are protected from the users in the other tiers.
- The following incumbents use all or part of the CBRS band:
  - **Navy radars:** Operational only on few ships & only need protection when they visit the harbors. The bandwidth of radar channels is only few MHz
  - **Satellite earth stations:** some but not all earth station and it is used in the 3600-3700 MHz chunk
  - **Wireless broadband service:** for enterprise users only in the 3650-3700 MHz chunk primarily using WiMAX technology. These links are extensively used by likes of utilities, transportation, etc.



Systems deployed within the neighborhood of an offshore Dynamic Protection Area (Courtesy NIST)

CBRS TIER 2

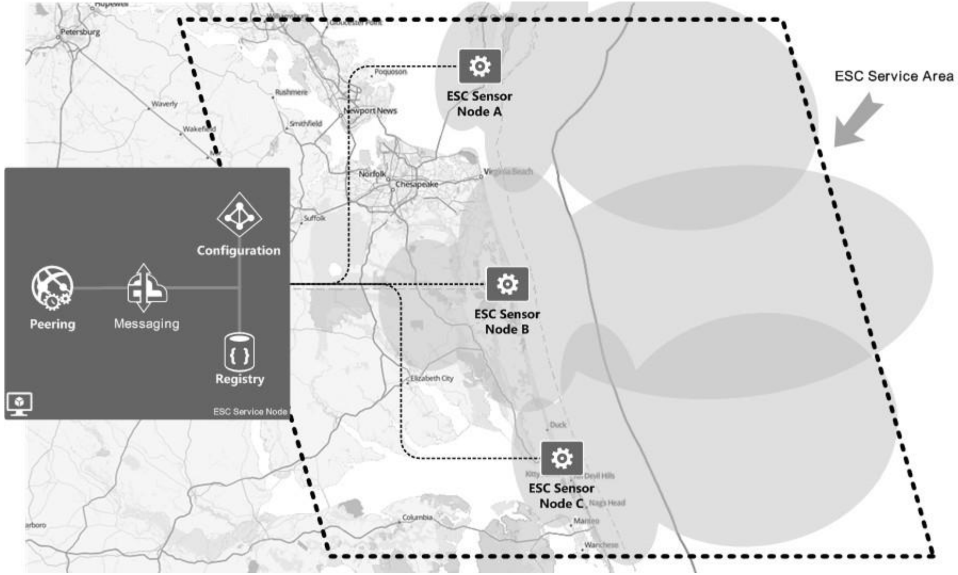
- **Tier 2: Priority Access License (PAL)**
  - PAL licenses were auctioned in 2020.
    - The PAL users have the second highest priority in the CBRS system
    - PAL users are protected from the GAA users.
- The following applies to PAL:
  - Up to 70 MHz is leased as PAL within 3550 – 3650 MHz frequency range
  - PAL licenses are leased per county
  - Lease term is 10 years
  - Each license is for a block of 10 MHz of bandwidth
  - No one entity can lease more than 4 channels in each county, for a total of 40 MHz

CBRS TIER 3

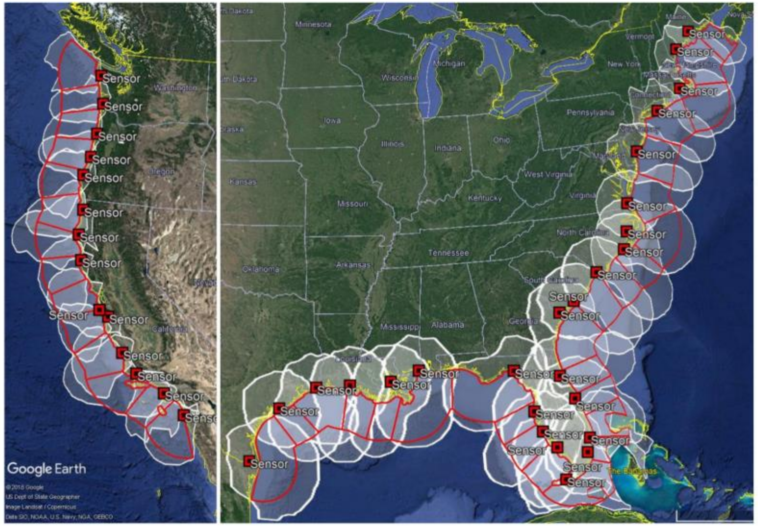
- **Tier 3: General Authorized Access (GAA)**
  - GAA users need to register for a nominal administrative fee
  - GAA users enjoy no protection from higher-tier users
- The following applies to GAA:
  - Up to 80 MHz is offered to GAA users within 3550 – 3700 MHz frequency range
  - GAA transmitting system need to bear the cost of an SAS

CBRS ENVIRONMENT SENSING

► Detects Spectrum usage by incumbent and transmits alerts to SAS



Example ESC (Courtesy Federated Wireless)



Coastal ESC's (Courtesy NIST)

FREQUENCY PLANNING REQUIRES GLOBAL COORDINATION

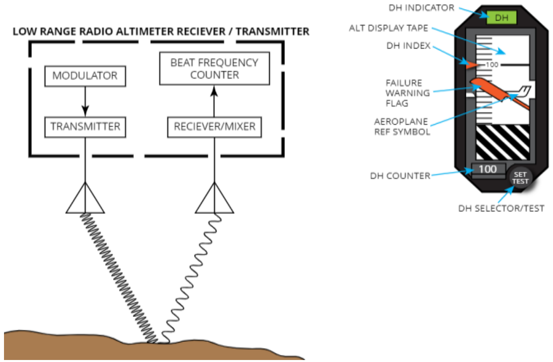
Table of Frequency Allocations — 3500-5460 MHz (SHF) — Page 41

International Table			United States Table		FCC Rule Part(s)
Region 1 Table	Region 2 Table	Region 3 Table	Federal Table	Non-Federal Table	
(See previous page)	3500-3600 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile 5.431B Radiolocation 5.433	3500-3600 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile 5.433A Radiolocation 5.433	3500-3550 RADIOLOCATION G59 AERONAUTICAL RADIONAVIGATION (ground-based) G110 US108	3500-3550 US108	
			3550-3650 RADIOLOCATION G59 AERONAUTICAL RADIONAVIGATION (ground-based) G110 US105 US107 US245 US433	3550-3600 FIXED MOBILE except aeronautical mobile US105 US433	Citizens Broadband (96)
3600-4200 FIXED FIXED-SATELLITE (space-to-Earth) Mobile	3600-3700 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile 5.434 Radiolocation 5.433	3600-3700 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile Radiolocation 5.435		3600-3650 FIXED FIXED-SATELLITE (space-to-Earth) US107 US245 MOBILE except aeronautical mobile US105 US433	Satellite Communications (25) Citizens Broadband (96)
			3650-3700 US109 US349	3650-3700 FIXED FIXED-SATELLITE (space-to-Earth) NG169 NG185 MOBILE except aeronautical mobile US109 US349	
	3700-4200 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile		3700-4200	3700-4000 FIXED MOBILE except aeronautical mobile NG182 NG457A	Wireless Communications (27)
				4000-4200 FIXED FIXED-SATELLITE (space-to-Earth) NG457A NG182	Satellite Communications (25)
4200-4400 AERONAUTICAL MOBILE (R) 5.436 AERONAUTICAL RADIONAVIGATION 5.438 5.437 5.439 5.440			4200-4400 AERONAUTICAL RADIONAVIGATION 5.440 US261		Aviation (87)
4400-4500 FIXED MOBILE 5.440A			4400-4940 FIXED MOBILE US113 US245 US342	4400-4500	
4500-4800 FIXED FIXED-SATELLITE (space-to-Earth) 5.441 MOBILE 5.440A				4500-4800 FIXED-SATELLITE (space-to-Earth) 5.441 US245	
4800-4990 FIXED MOBILE 5.440A 5.441A 5.441B 5.442 Radio astronomy 5.149 5.339 5.443				4800-4940 US113 US342	
			4940-4990 5.339 US342 US385 G122	4940-4990 FIXED MOBILE except aeronautical mobile 5.339 US342 US385	Public Safety Land Mobile (90Y)
4990-5000 FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY Space research (passive) 5.149			4990-5000 RADIO ASTRONOMY US74 Space research (passive) US246		

RADAR ALTIMETER AND C-BAND

- An example of where things didn't quite work out as intended!
- RADAR Altimeters (RA) operate in the 4.2 to 4.4 GHz frequency range
- Most RA's use Frequency Modulated Continuous Wave (FMCW), but some are pulsed
- An RA is a downward pointing RADAR that is used to detect the height of the airplane above terrain
- Most useful in degraded visual environments where it augments autoland systems
- Also used to augment Enhanced Ground Proximity Warning System (EWGPS)

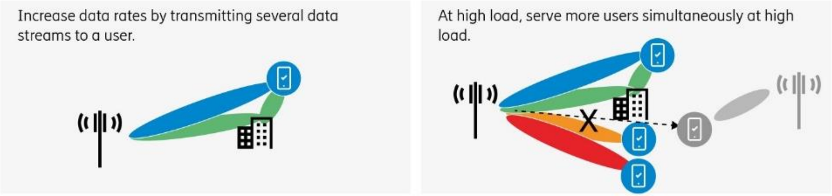
Radar altimeter location (Courtesy quora.com)



RA Block diagram (Courtesy answeringatpl.com)

5G TECHNOLOGY

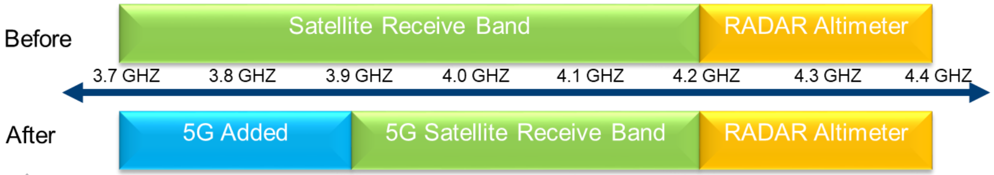
- Directivity is not a simple ISOTROPHIC model
- 5G gNodeB designs in C-Band typically are:
  - 64Tx, 64Rx design (some are 32Tx, 32Rx)
  - All use some type of hybrid or digital beam forming
    - Note the profiles used by RTCA used 8T and 16T AAS
  - Horizontal BW 15°
  - Vertical BW 6°
  - Nominally **3.125 W per port** or 200 W max RF power (for 64T)
  - IBW = 200 MHz
  - OBW = 100 MHz

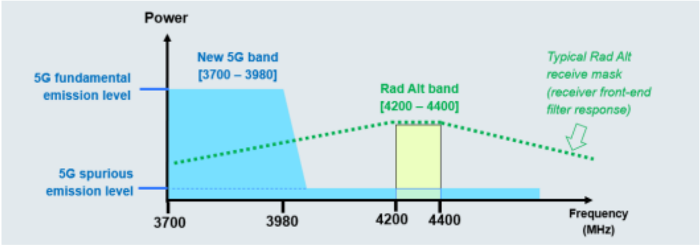


Each gNodeB vendor can implement differing MIMO and beamsteering techniques (SU-MIMO, MU-MIMO, single SSB)

RADAR ALTIMETERS

- FCC auctioned off spectrum in the C-Band from 3.7 GHz to 3.98 GHz for a future 5G/LTE band
- However…
  - RA requirements were defined in TSO-C87 in **1966** and became part of RTCS CO-155 MOPS in **1974**
    - Replaced by TSO-87A in **2012**
  - Future RTCS SC-239 working on an updated MOPS that will include improved interference mitigation, but does not address the ~11,800 transport category airplanes that could be affected
  - Older RA’s had a very wide receive mask, which could allow interference from 5G C-band
    - None of these specifications have requirements for receiver masks or susceptibility to interference – merely interoperability
    - RA’s were never designed or intended to work with modern RF spectrum allocations
      - Archaic set of standards not up to modern telecommunications requirements
    - RA are wideband and have zero requirement for RFFE rejection and are susceptible to blocking in the receiver



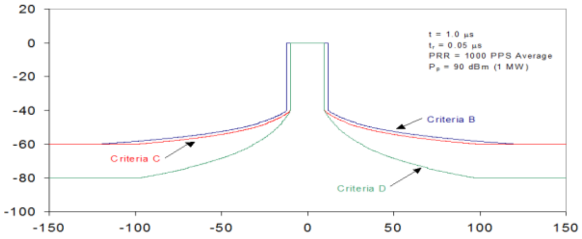


RA Receive mask (Courtesy RTCA.org)

SO WHAT'S THE PROBLEM?

- ITU-R and NTIA have several publications on radar measurements and coexistence
  - Measurement Guidelines
    - RSEC & ITU-R M1177-4
  - Mitigation Policy
    - ITU-R M-1461, SM377-6 & P.1546-1
- Publications only consider the impact of radar Tx on the cellular infrastructure Rx, however the relationship of the radar Rx to the cellular Tx is not reciprocal.
- Measurement of the actual RA receiver blocking is vital to assure operation close to 5G C-band base stations
- Blocking and interference testing has indicated that some pulsed RAs are more vulnerable than FMCW RA's

RSEC EMISSION MASK



"The fundamental emissions may lead to blocking interference in the radar altimeter receiver, wherein ***a strong signal outside of the normal receive bandwidth cannot be sufficiently filtered in the receiver*** *to prevent front-end overload or other effects. The spurious emissions, on the other hand, fall within the normal receive bandwidth of the radar altimeter, and may produce undesirable effects such as desensitization due to reduced signal-to-interference-plus-noise ratio (SINR), or false altitude determination due to the erroneous detection of the interference signal as a radar return."*
RTCA -274 -20 / PMC -2073 report from October 7, 2020

REVIEW OF 5G C-BAND AND RADIO ALTIMETER

- ICAO – working paper
  - FSMP-WG11 WP/30 (March 12, 2021) readdressed the prior report from 2012 to include 5G technologies
  - Included 5G technology beamforming, directivity and sidelobe performance
  - Assessed FMCW and Pulsed RA technologies
  - Considered different BS deployment models for dense urban, urban, and rural deployments
  - Considered both Airport & Helipad/Emergency facilities compatibility

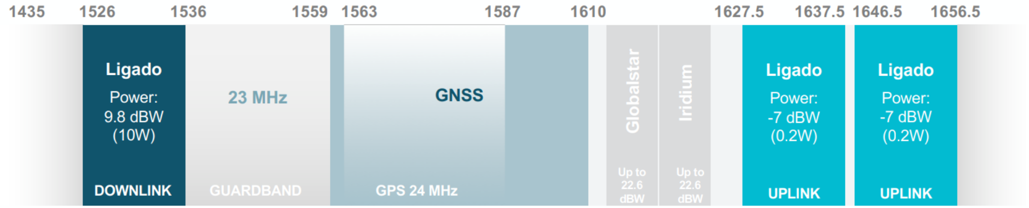
Type of Interference	Threshold Value
Unwanted emission interference	-117 dBm/MHz
Blocking	-54 dBm

RADAR ALTIMETERS – THE SOLUTION

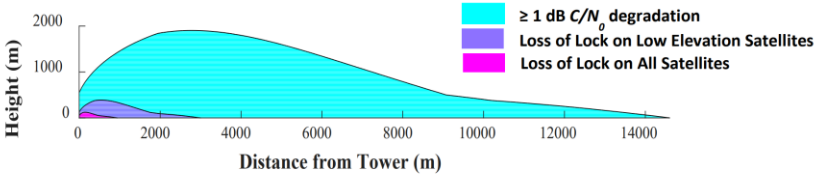
- Test with real-world scenarios in controlled environments
- Test & develop rules before selling spectrum
- Consider regional variations (e.g. Japanese C-band has only 100 MHz of guard band vs. 200 MHz in USA
- Retrofit current RA’s with improved rejection filters (still needs to be re-certified = $$)
- Retrofit affected airplanes with improved RA’s
- Locate base-stations away from airports and helipads (e.g. hospitals)
  - Use micro cell with lower power if close to active airplane operations
  - Suggested separation - 50 m for macro-cell and 20m for small-cell
- Beam-form base-station emissions away from airports and helipads
- Improved inter-agency coordination - FCC & FAA

GPS INTERFERENCE

- In April 2020, the FCC licensed the 1.526-1.536 GHz spectrum in the L-Band to Ligado (formerly LightSquared) for 5G terrestrial and satellite communications
- This is very close to the GNSS L1 band & sits between L1 & L2
- GNSS is deemed critical infrastructure and generates >$1B in economic activity in the USA every day
- Interference with GPS receivers has been documented



Impact of a 29 dBW Cellular Base Station Transmitting at 1530 MHz on a High Precision GPS/GNSS Receiver



THE PROBLEM

- Multi-band GNSS receivers do not typically filter the whitespace between L1 & L2
- The generally accepted 1 dB C/N_0 interference criterion was ignored by the FCC in favor of a “harmful interference” criteria and “performance based metrics” which are undefined and arbitrary
  - FCC has used the 1 dB criteria in other situations, such as the C-band satellite downlink protection from terrestrial 5G broadband (FCC 20-22)
- Ligado’s core argument is that it is operating inside its licensed band and it’s the GPS receiver that is susceptible to out-of-band interference
  - Whilst true, it is important to note that GPS receivers are the incumbent and were developed before testing for co-channel interference was widely adopted
  - GPS receiver designers assumed that there would be no adjacent high powered transmission “Quiet Zone”
- The DOT Adjacent Band Compatibility tests clearly demonstrated widespread disruption by Ligado @10W TX Pwr
  - Transmitters were at every other block corner
  - GPS users typically 20 to 200 meters away from transmitter
- Interference more likely with military M-code and Iridium SATCOM systems

COEXISTENCE TESTING

TESTING & STRATEGIES FOR MITIGATION

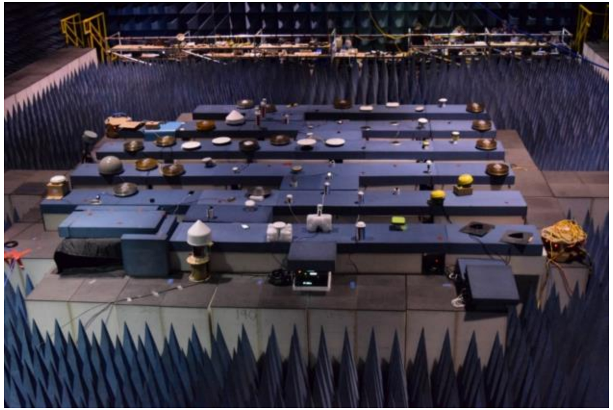
- **Modelling & Simulation**
  - Useful but challenging to fully model a real-world environment
  - Can be useful during R&D phase of product development
  - Prediction of performance metric - “Likelihood Of Coexistence” (LOC)

- **Model Inputs**
  - Strength & quality of intended signal(s)
  - EM fields in operational environment
  - Variations outside of physical layer (e.g. in the network)
  - Estimation of where and mode of failure
  - Quality of model is predicated on quality of input data
    - Garbage in = garbage out!

TESTING & STRATEGIES FOR MITIGATION CONT'D

- **Real-world testing**
  - Good for final sanity check
  - Limited ability to cover all potential use-cases
  - Uncontrolled environment
  - Last step, not first…

- **Functional & performance testing in a controlled environment**
  - Repeatable & automatable
  - Can cover a large number of use cases
  - Regression testing is relatively simple to implement
  - Realistic RF environments can be complex to implement
  - Monitoring of RF environment is key (Spectrum Analyzer/VSA)



GPS/GNSS receiver test at White Sands Missile Range Anechoic Chamber
(courtesy US Army)

IEEE/ANSI C63.27

- Evolving standard for Evaluation of Wireless Coexistence
- Standard outlines evaluation process and supporting test methods for:
  - Test setup
  - Verification of the test setup
  - Establishing the intended RF communication of the EUT in an appropriate RF channel
  - Verification of the unintended signal
  - Exposing the EUT to the unintended signal
  - Evaluating the ability of the EUT to maintain its Functional Wireless Performance (FWP) under the conditions of the test and assess the effect of the EUT communication of the unintended signals
- 4 measurement methods are outlined
  - Conducted
  - Multiple chamber
  - Radiated anechoic chamber
  - Radiated open environment

CONTROLLED ENVIRONMENT TESTING

- Over The Air (OTA) testing to create realistic RF operating conditions
- Performed in an initially pure & quite RF environment - most commonly an anechoic chamber
  - Some tests can be performed on an outdoor range
    - Especially for long-distances or higher power testing (e.g. RADAR)
- Test system needs to be able to generate any required RF signal (LTE, WIFI, DVB-X, 5G NR, RADAR, FMCW, GNSS, etc.)
  - Libraries of commercial signals
  - Long duration desirable
  - Deterministic latency
- Measurement, DUT control & automation
  - Enables regression testing
- Storage of measured results
- Post-acquisition analysis software
- Channel modelling (beamforming, doppler, multipath, fading, environmental, etc.)
- Mechanical control of antennas & test samples to change orientation of emitter, interferer & DUT

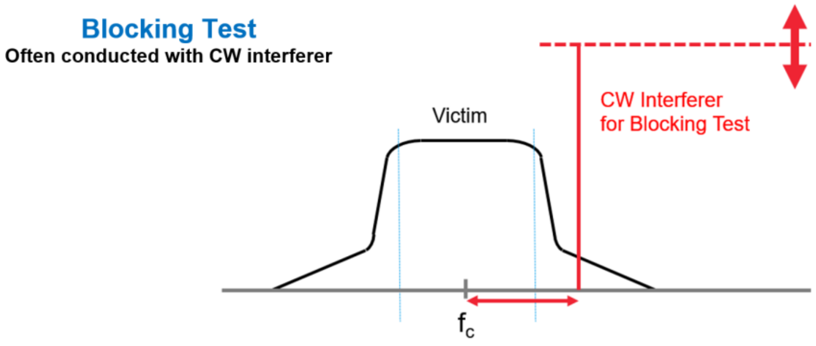
KEY PERFORMANCE METRICS & COMMON MEASUREMENTS

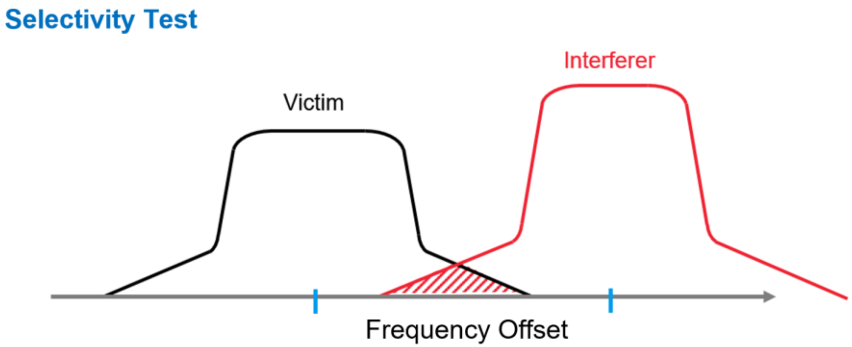
Enables comparative measurements

- **Tx**
  - Adjacent Channel Leakage Ratio (ACLR)
  - Adjacent Channel Power Ratio (ACPR)
  - Receiver Sensitivity
  - Error Vector Magnitude (EVM)
- **Rx**
  - Throughput
  - Latency
  - Jitter
  - Bit Error Rate (BER)
  - Packet Error Rate (PER)
  - Threshold Of Communication (TOC)
  - Device Under Test, Signal To Interference Ratio (DUT SIR)
  - RADAR – Minimum Detectable Signal, Frequency Dependent Rejection (FDR) - On Tune Rejection and Off-Frequency Rejection

DEFINING PERFORMANCE

- Blocking Test – Typically a 2dB compression point of front end LNA
- Selectivity Test – A 3dB increase in the SNR bleeding into IF due to adjacent channel

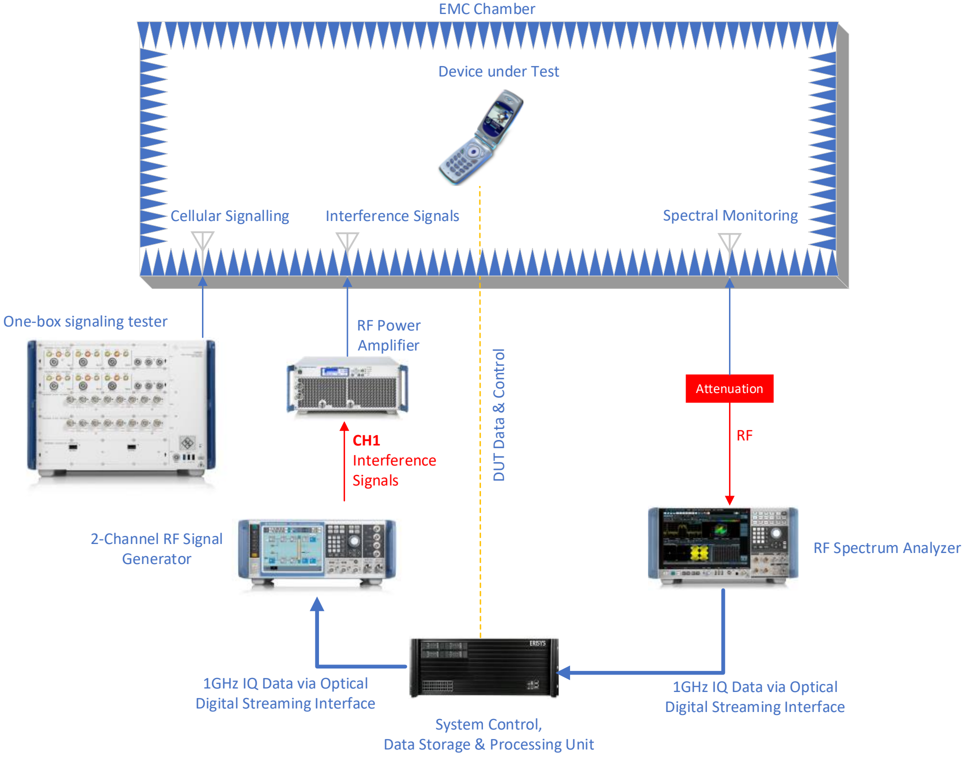




OPEN-LOOP TESTING

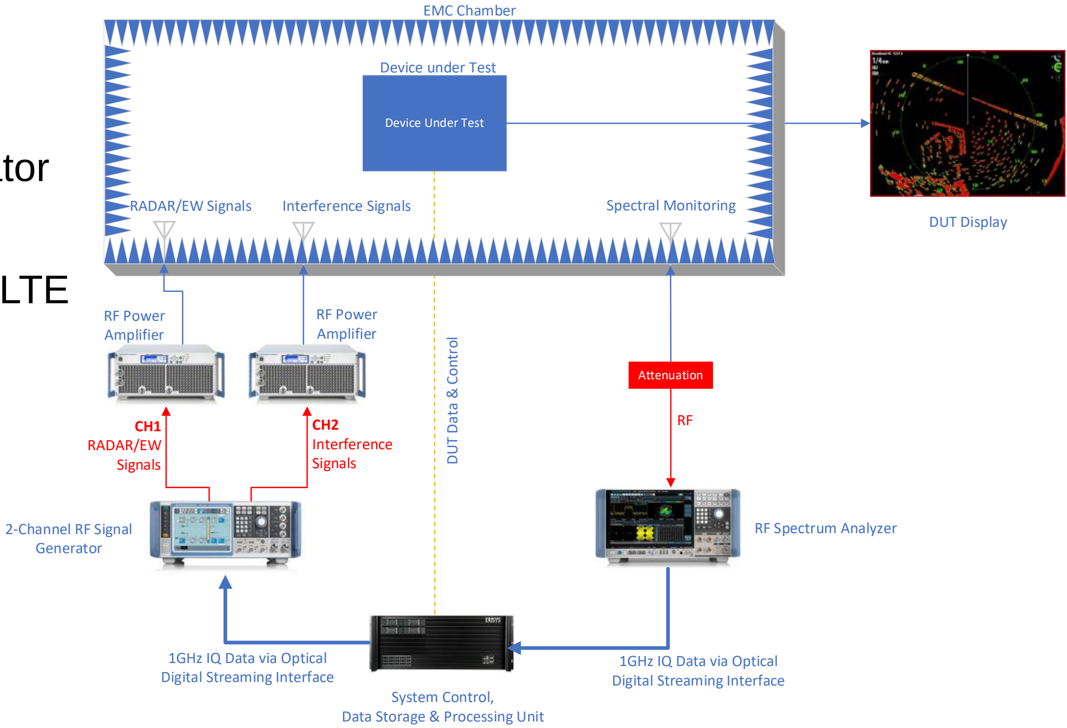
- Example – SATCOM, GNSS receiver, cellular
  - DUT has inbuilt quality of service metrics
- Full coded signaling test
- Typically only RX testing

- One box signaling tester creates an actual call with the DUT (for cellular)
- Channel 1 has interference signals, i.e. RADAR

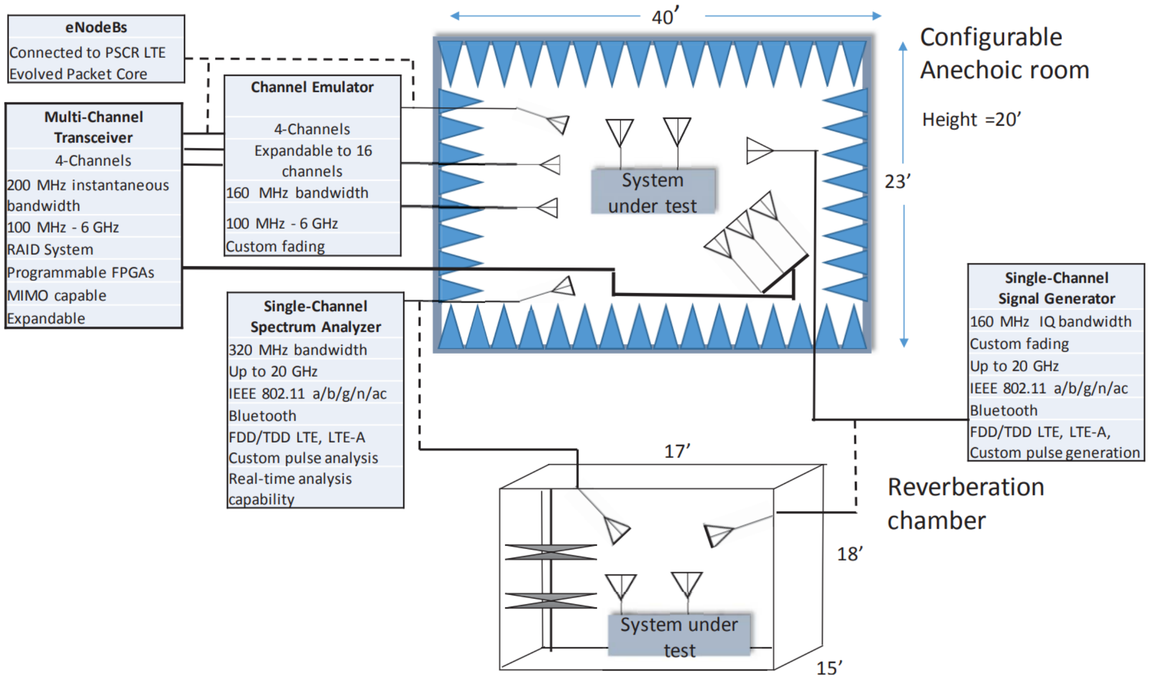


CLOSED LOOP TESTING

- Example – RADAR, Telemetry
- DUT has no intrinsic reporting metrics
- More complex environmental model
  - Delay, doppler, multipath, latency
  - Generated within the RF signal generator
- Channel 1 is a RADAR target simulator
- Channel 2 is the interference signals, i.e LTE

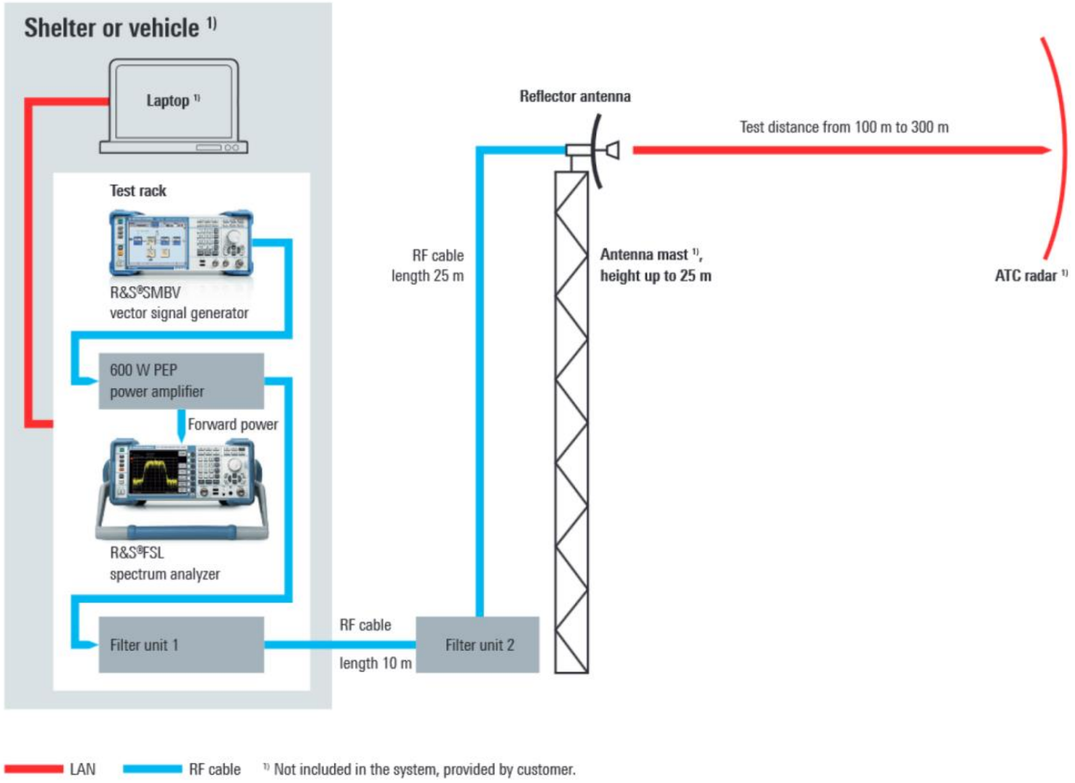


CONTROLLED ENVIRONMENT TEST EXAMPLE – NIST NBIT



NIST Broadband Interoperability Test Facility: NBIT 1.0 (Courtesy NIST)

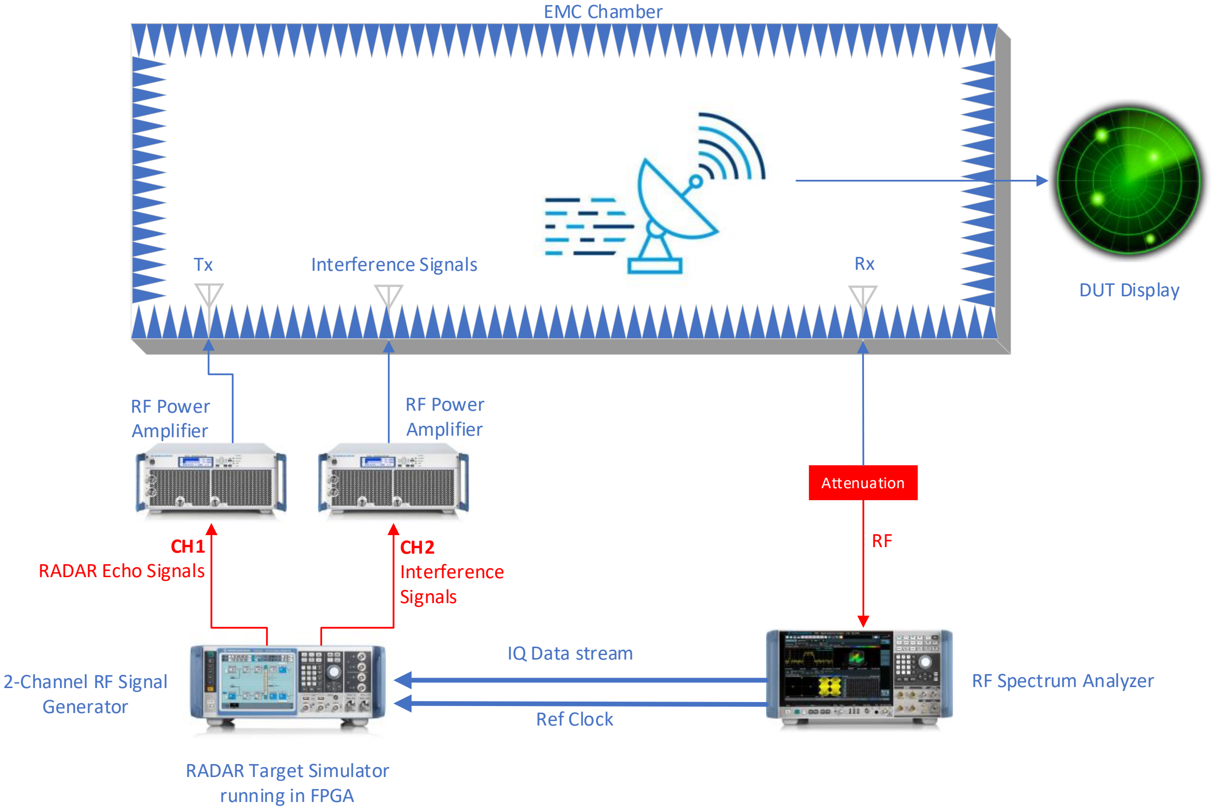
RANGE TEST DIAGRAM (LTE S-BAND ON ATC RADAR)



RADAR & LTE COEXISTENCE

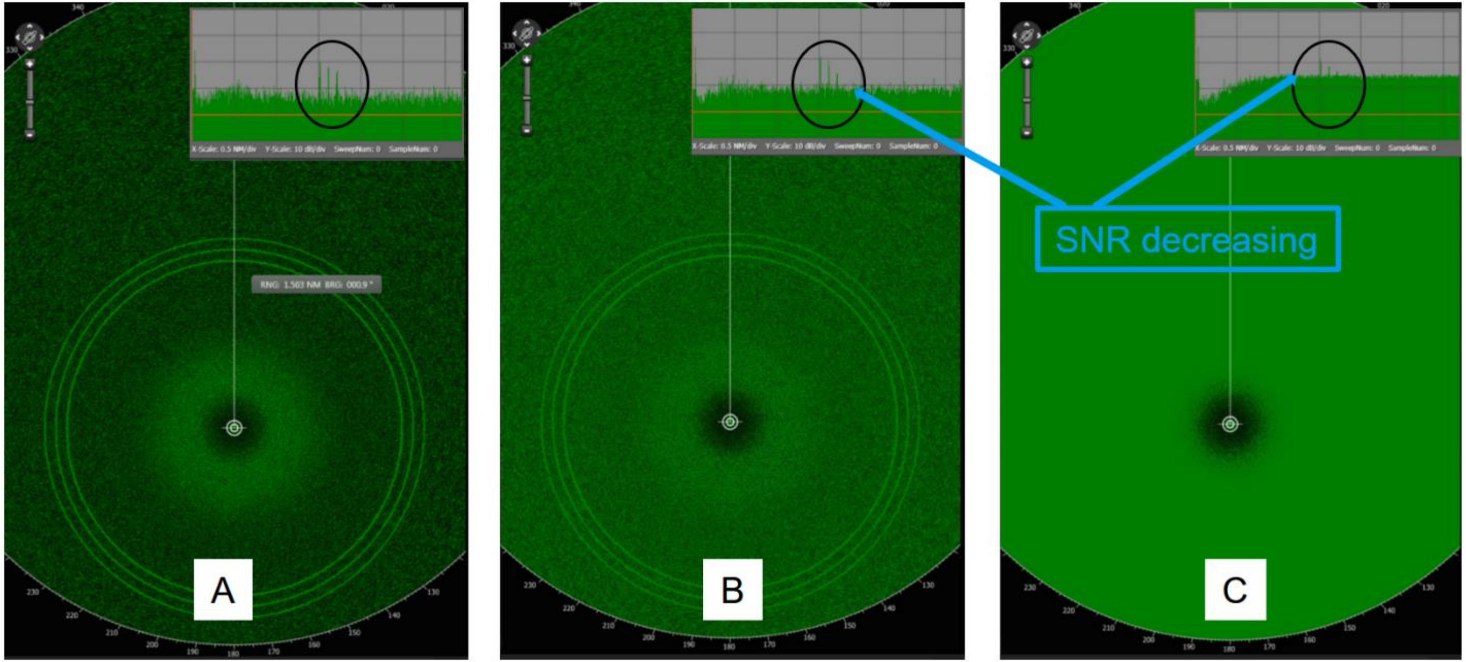
- Real world test of radar operation in the presence of interference signals
- Key Performance Indicator (KPI) is Frequency Dependent Rejection (FDR)
  - Measure of IF selectivity – $OFR_{outband}$ (Off Frequency Rejection – Out of Band)
- Key interference parameters
  - **Blocking** - Measure of gain compression at the front-end LNA due to a strong signal forcing the LNA into nonlinear compression
  - **Selectivity** - Measure of the increase in noise introduced into the receiver front-end while not in non-linear compression, that will reduce the signal-to-noise ratio (SNR) of the receiver
- RADAR Echo Generator (REG) used to create both the delayed returns simulating target(s) as well as the interference signal(s), which could be CW, noise, LTE and IQ-based arbitrary waveforms

TEST SYSTEM BLOCK DIAGRAM



RADAR SELECTIVITY RESULTS

Decreasing SNR due to the interference signal appears as increasing the baseline noise

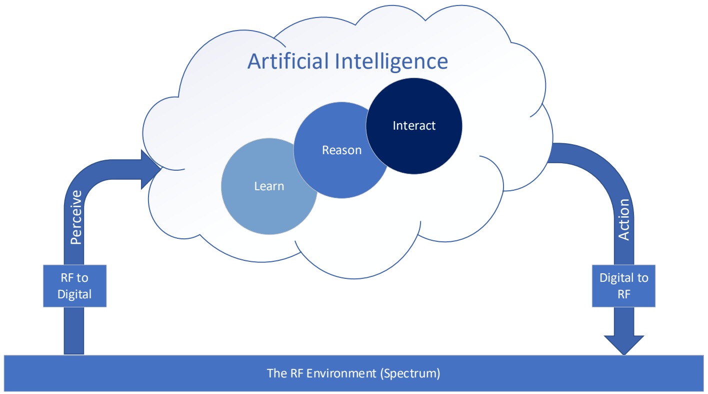


RESULTS

- Performance of Cellular Base stations and Radars are vastly different!
- A typical base station can reject a +63dB signal at a fractional bandwidth of 0.25% at ANY frequency allocated! At 4 GHz, this is a 10 MHz offset!
- The selectivity of the radar has a much greater sensitivity at a much greater frequency offset.
  - This affects the frequency allocation guard band between the radar and wireless services
- Assuming a cellular base station power in band 41 (2.495 – 2.690 GHz) at 40 W (+46dBm)
  - Cellular base station would have a free space attenuation of ~-116 dB at 6 km.
  - A possible band 41 downlink signal at 2690 MHz represents a -0.37 percent offset for a radar with a center frequency of 2.7 GHz.
  - Knowing the FDR behavior of the victim radar, a 3% fractional bandwidth would dictate the radar should not be operated at a frequency below 2.78 GHz at this 6km distance

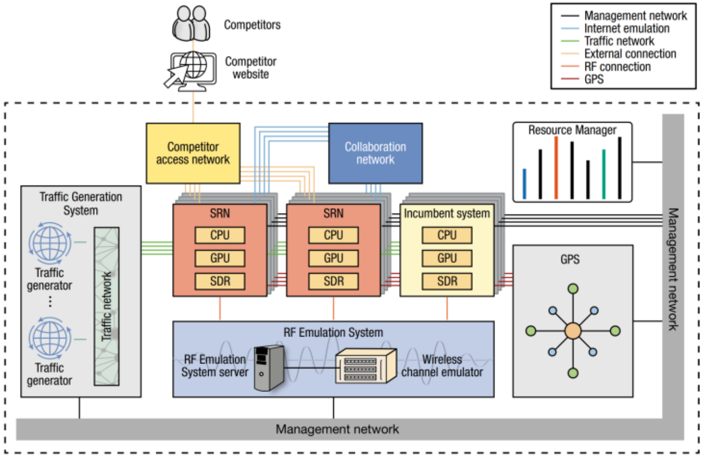
COGNITIVE COEXISTENCE SYSTEMS

- A cognitive based coexistence system perceives & interacts with the RF environment
  - System converts the RF spectrum and associated energy into a stream of RF IQ data
- Uses Artificial Intelligence (AI) & Machine Learning (ML)
  - Makes autonomous decisions
  - Determines a course of action without recourse to any other systems or any human intervention
- A cognitive system uses a continuous loop
  - Situational perception
  - Learning
  - Reasoning
  - Interaction
  - Action
- The system learns & adapts from its interactions with the RF environment



DARPA SPECTRUM COLLABORATION CHALLENGE

- SC2 was designed to encourage researchers to develop smart systems that collaboratively, rather than competitively, adapt in real time to the fast-changing, congested spectrum environment
- The primary goal of SC2 was to enable radios with advanced machine-learning capabilities to collaboratively implement strategies that optimize use of the wireless spectrum in ways not possible with today's intrinsically inefficient approach of pre-allocating exclusive access to designated frequencies



DARPA SC2 System & Block Diagram (Courtesy DARPA)

SUMMARY

- The need for coexistence testing has never been greater
- Real-world OTA testing is imperative
  - Closed loop functional test OTA with realistic scenarios
- Arbitrary & flexible wideband signal generation needed to address future fully-coded modulation requirements
  - Allows bifurcation of TX and Rx sides of comms link
- Higher frequencies complicate guard-bands & filtering challenges
- New challenges are always occurring
  - 3GPP TR 38.820 is looking to define FR3 spectrum @ 7-24 GHz
    - Airport Surface Movement Radar (SMR) is used for traffic safety using either 9 GHz or 15-17 GHz frequencies….
- 6G is coming… >100 GHz is the wild-west!
- Cognitive AI/ML is an ever-evolving technology to improve spectral sharing & coexistence

THANK YOU FOR YOUR TIME

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