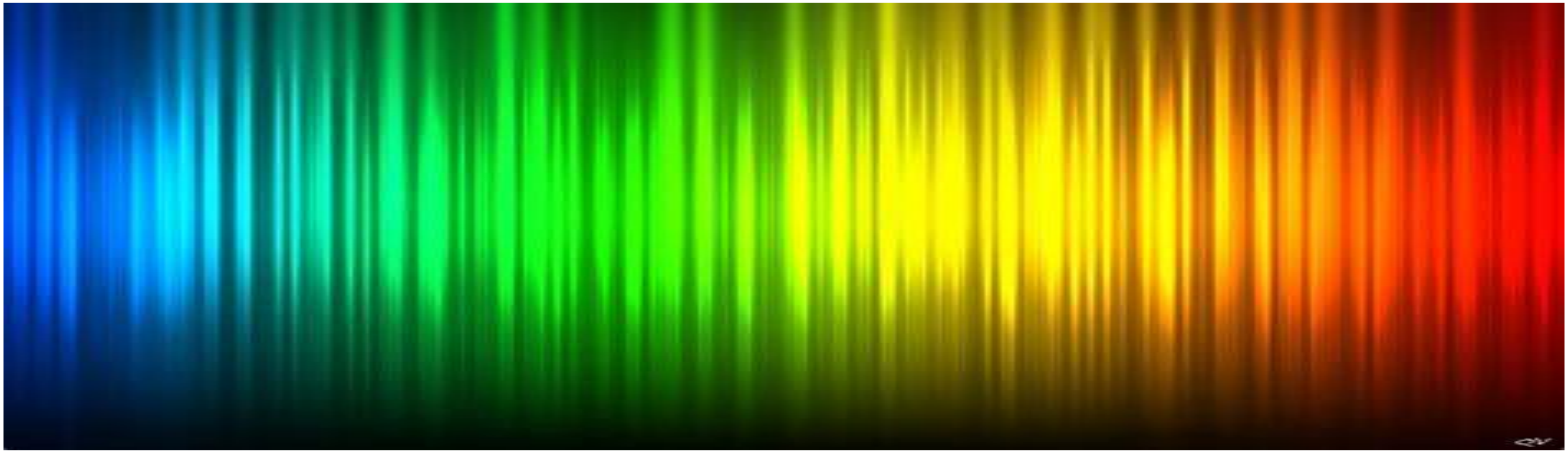
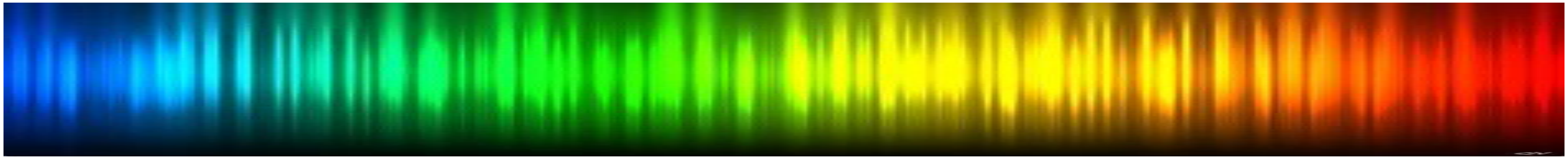
Spectrum ....
..................................Be Prepared for Sharing



Contributors



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Overview

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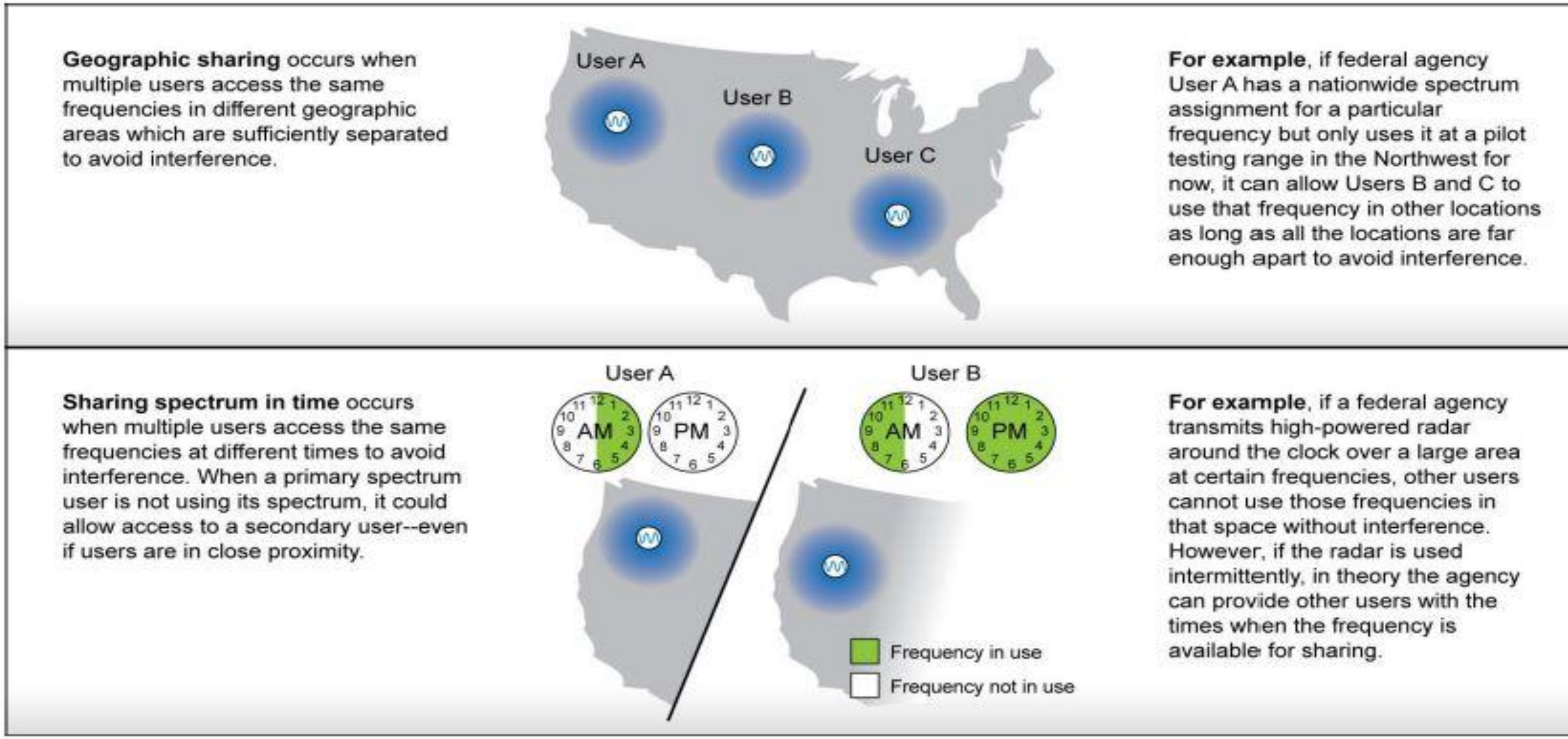
Straw Poll for Questions at the End of this Tutorial

- Is the IEEE 802 Community interested in accessing Shared Spectrum?
- Is the IEEE 802 Community interested in Shared Spectrum Solutions for 5G?
- There are three initial steps to turn Spectrum Sharing Technologies into Standards – IEEE 802 Executive Committee Study Group, Working Group Study Group or Industry Connections Activity
    - Should we form an EC Study Group to understand the problem of Spectrum Sharing and follow-up Activities?
    - Should we form a WG Study Group to understand the problem of Spectrum Sharing and follow-up Activities?
    - Should we form an Industry Connections Activity for Spectrum Sharing and follow-up Activities?
- Should IEEE 802 engage in creation of a Protocol to Access the Spectrum Database (Spectrum Access System)? (e. g. IETF Protocol to Access White Spaces - PAWS)
- Should IEEE 802 engage in creation of a standards for Beaconing?
- Which of the 5G bands are of most interest to the IEEE 802 Community?

What is Bi-directional Spectrum Sharing

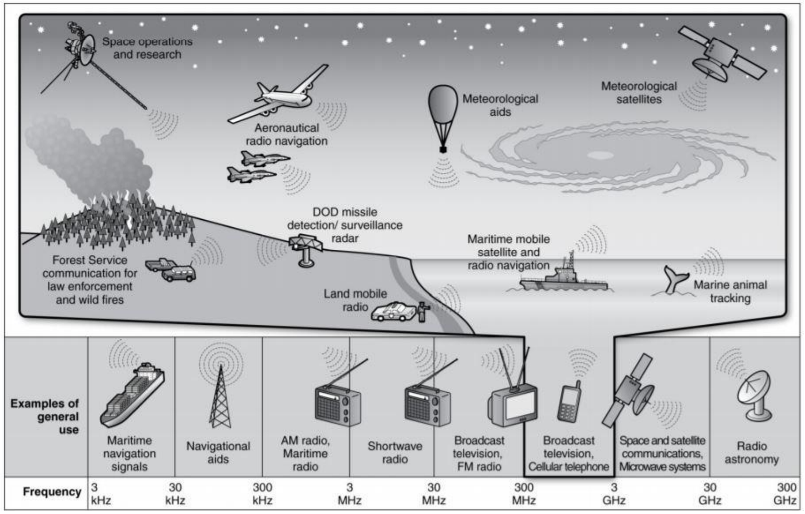


https://www.gao.gov/assets/650/648206.pdf

Sharing of the Same Spectrum based on Location or Time to avoid interference to a Primary User

Federal to Commercial Bi-directional Spectrum Sharing

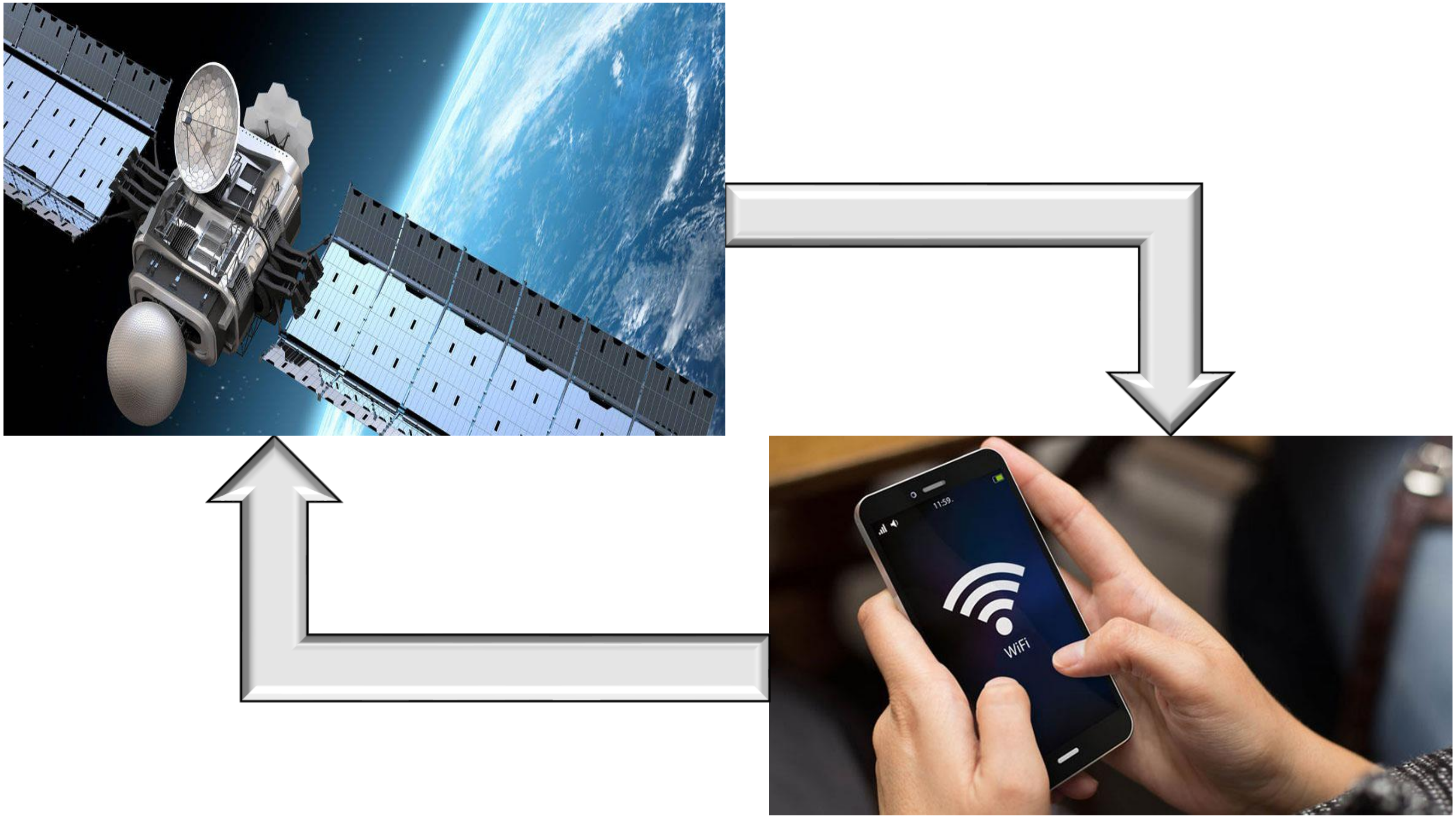
Federal



Commercial

Commercial to Commercial Bi-directional Spectrum Sharing

Commercial 1



Commercial 2

Spectrum Bands being Considered for Commercial Use

Presenter
Apurva N. Mody, National Spectrum Consortium

On behalf of
Julie Knapp, Chief of Office of Engineering and Technology, FCC

Jay Holcomb, Itron, Chair, IEEE 802.18 Radio Regulatory TAG

Mobile Now Act and Spectrum Bands Being Considered for Release

Julius Knapp, Chief
Office of Engineering and Technology
Federal Communications Commission

Presented to the
National Spectrum Consortium
November 1, 2018

Note: The views expressed in this presentation are those of the author and may not necessarily represent the views of the Federal Communications Commission

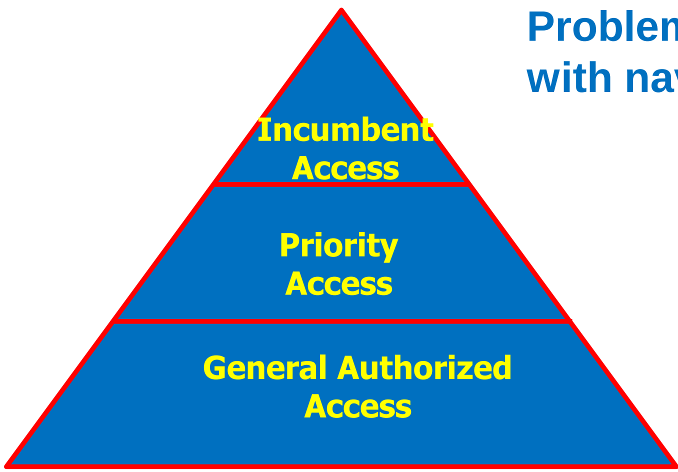
Key FCC Spectrum Initiatives & Proceedings

- **Low Frequency Spectrum:**
  - TV Broadcast Incentive Auction (600 MHz band)
- **Mid Frequency Spectrum:**
  - 3.5 GHz (3550-3700 MHz)
  - Proposal for 3700 – 4200 MHz
  - Draft proposal for 5925 – 7125 MHz
- **High Frequency Spectrum:**
  - Spectrum Frontiers (above 24 GHz)
  - Spectrum Horizons (above 95 GHz)

All these bands require mechanisms for spectrum sharing

Mid Band

Citizen's Broadband Radio Service (3.5 GHz)



Spectrum sharing across three tiers

Problem: How to share spectrum (3550 – 3700 MHz) with navy radars other incumbent users

Spectrum Access System (SAS) protects against interference and manages access to spectrum

Dynamic Spectrum Access

<u>Where We Are In The Process</u>

- **Multi-stakeholder process -** WinnForum developing implementation
- **Conditionally approved first Spectrum Access Administrators**: Amdocs; Comsearch, CTIA, Federated Wireless, Google; Key Bridge; and Sony
- **SAS testing by NTIA** Institute for Telecommunications Science
- **Initial commercial deployments** – Applications under review by FCC

FCC planning to open 3.4 GHz to 4.2 GHz in the near future.

Mid Band
3.7 & 6 GHz

- Proposed to make spectrum available for licensed wireless service the in the **3.7 – 4.2 GHz C-band satellite DL band**
- Proposed to make spectrum available for unlicensed access in the 5.925 – 7.125 GHz (6 GHz) band
- **Significance**:
  - **3.7 GHz is adjacent to 3.5 GHz band - region is focus for 5G internationally**
  - 6 GHz is close to 5 GHz unlicensed bands

Two Areas of Focus:

3.7 – 4.2 GHz – Proposed licensed access to C-band satellite DL spectrum

5.925 – 7.125 GHz – Proposed unlicensed sharing with Pt-2-Pt microwave & satellite uplinks

3.7 GHz to 4.2 GHz will require sharing with Fixed Satellite Receivers

6 GHz Spectrum Sharing Requirements

Interested parties, in or adjacent to the 6 GHz band:

- Auto Makers, Broadcast, Microwave users in general, Public Safety, RLANs, Satellite, Utilities, UWB
- The 6 GHz band is exclusive non-federal spectrum and is host to several incumbent services operating on a primary basis, including fixed point-to-point services, Fixed-Satellite Service (FSS), Broadcast Auxiliary Service, and Cable Television Relay Service. A query of FCC databases shows 47,695 unique call signs between 5.925 and 7.125 GHz.

NPRM band segments:

Band (GHz)	Primary Allocations	Reference used in this NPRM[63]	Devices
5.925-6.425	Fixed Service FSS	U-NII-5	Standard-Power Access Point
6.425-6.525	Mobile Service FSS	U-NII-6	Low-Power Access Point
6.525-6.875	Fixed Service FSS	U-NII-7	Standard-Power Access Point
6.875-7.125	Fixed Service Mobile Service FSS[64]	U-NII-8	Low-Power Access Point

6 GHz requires spectrum sharing with Microwave Links, Broadcast Auxiliary Services, Fixed Satellite Receiver Stations etc.

6 GHz Spectrum Sharing Requirements

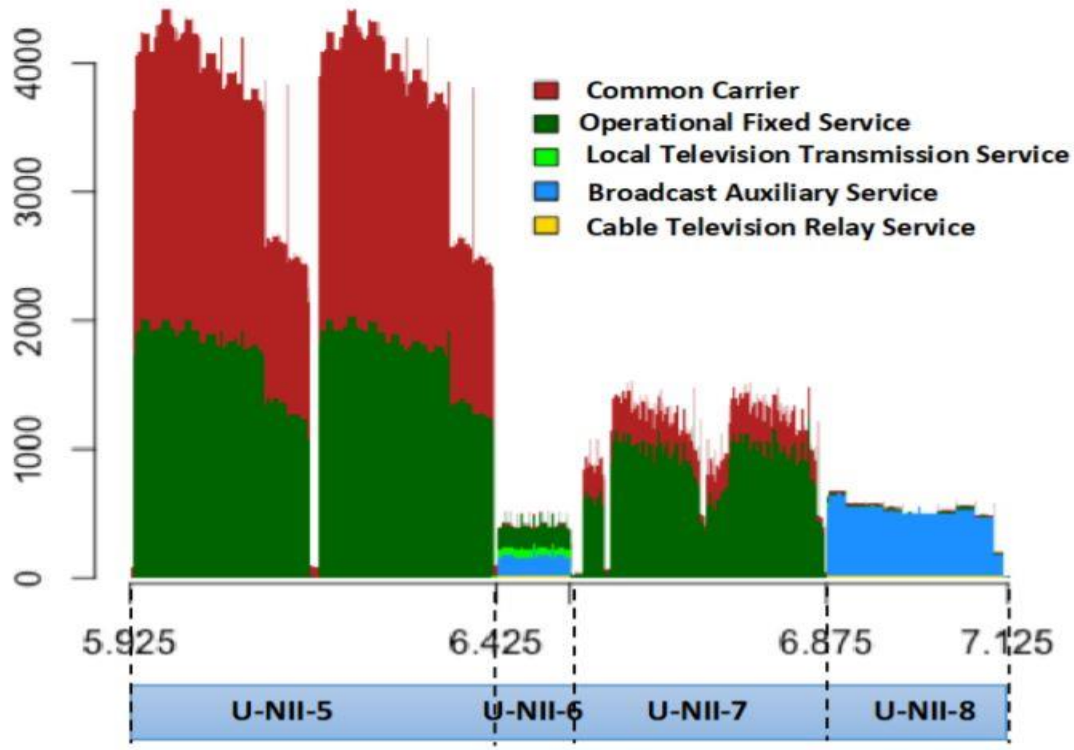
Sharing is focusing on AFC – Automated Frequency Coordination

- In the 5.925-6.425 GHz and 6.525-6.875 GHz sub-bands, unlicensed devices would only be allowed to transmit under the control of an automated frequency control (AFC) system. AFC is nothing but a fancier Spectrum Database
  - These frequencies are heavily used by point-to-point microwave links and some fixed satellite systems.
  - The AFC system would identify frequencies on which unlicensed devices could operate without causing harmful interference to fixed point-to-point microwave receivers.
- In the 6.425-6.525 GHz and 6.875-7.125 GHz sub-bands, unlicensed devices would be restricted to indoor use and would operate at lower power, without an AFC system.
  - These frequencies are used for mobile services, such as the Broadcast Auxiliary Service and Cable Television Relay Service, as well as fixed and fixed satellite services. The itinerant nature of the mobile services makes the use of an AFC system impractical.
  - The combination of lower power and indoor operations would protect licensed services operating on these frequencies from harmful interference.

6 GHz requires spectrum sharing with Microwave Links, Broadcast Auxiliary Services, Fixed Satellite Receiver Stations etc.

6 GHz Spectrum Sharing Requirements

Sharing is focusing on AFC – Automated Frequency Coordination



6 GHz requires spectrum sharing with Microwave Links, Broadcast Auxiliary Services, Fixed Satellite Receiver Stations etc.

High Band
Spectrum Frontiers

Spectrum Allocations

- 12.55 GHz of Spectrum added for mobile
  - **Licensed Bands (Total 3.85 GHz):** 24.25-24.45 GHz and 24.75-25.25 GHz; 47.2-48.2 GHz; 27.5-28.35 GHz; 37-38.6 GHz; 38.6-40 GHz;
  - **Unlicensed Bands (Total 7 GHz):** 64-71 GHz (added to 57 – 64 GHz)

Service Rules

- Part 30: Upper Microwave Flexible Use Service (UMFUS)
- Geographic Area Licensing, Area Size, Band Plan, License Term, Overlay Auctions
- Technical rules
- Performance Requirements

Often Associated with "5G"

Overview of First Report and Order Bands

	28 GHz	37 GHz	39 GHz	64-71 GHz
Frequency	27.5-28.35 GHz	37-38.6 GHz	38.6-40 GHz	64-71 GHz
Bandwidth	850 MHz	1600 MHz	1400 MHz	7000 MHz
Terrestrial Allocation	Licensed for fixed operations, with about 75% of the population covered by existing licenses; remaining licenses in inventory	Yes (no current use)	Licensed for fixed operations, with about 50% of the population covered by existing licenses; the remaining licenses are in inventory.	Yes (no current use)
Federal Allocation	No	Radio Astronomy / Space Research in 37-38 GHz @ 3 sites; Federal Fixed/Mobile in 37-38.6 GHz @ 14 locations	Fixed Satellite Service / Mobile Satellite Service in 39.5-40 (military use only)	Earth Exploration Satellite Fixed/Mobile/Satellite
Satellite Allocation	Yes	Yes (no current use)	Yes (no current use)	Yes (no current use)
Licensing Scheme	Licensed	Licensed	Licensed	Unlicensed

Satellite/terrestrial sharing accomplished by well defined protections & rights

Lower 600 MHz identified for sharing between Federal Government and Private Sector - - invited comment on sharing method

Overview of Second R&O Bands

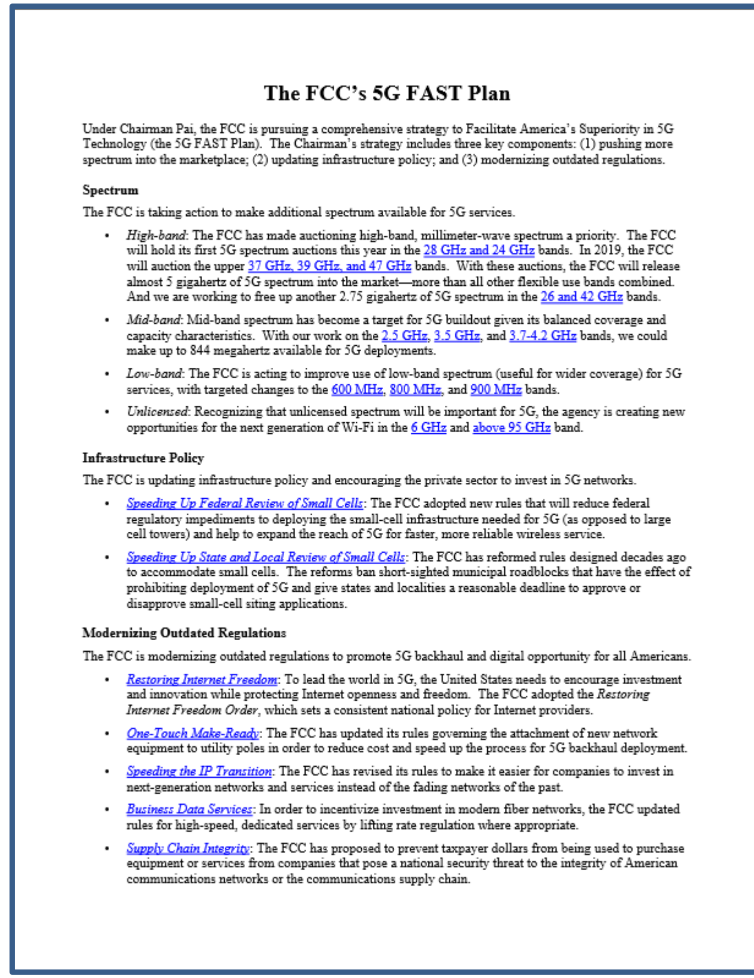
	24 GHz	*47 GHz*
Frequency	24.25-24.45 GHz and 24.75-25.25 GHz	47.2-48.2 GHz
Bandwidth	700 MHz	1000 MHz
Terrestrial Allocation	Lower segment is licensed for two types of fixed operations: 24 GHz service and Digital Electronic Messaging Service (DEMS). 5 active 24 GHz licenses, and 38 active DEMS licenses; remaining licenses in inventory	Yes (no current use)
Federal Allocation	No	No
Satellite Allocation	Yes, 24.75-25.25 GHz band segment is non-Federal allocated for FSS (Earth-to-space)	Yes (no current use and the Commission designated this band for terrestrial use)
Licensing Scheme	Licensed	Licensed

Roll-out of MMW Bands & 5G

- Already happening - - granted flexibility for incumbent fixed services to offer mobile

- Auctions planned this year for 28 GHz, then 24 GHz; upper 37 GHz, 39 GHz & 47 GHz next year

- Third Notice invited comment on 25.25-27.5 GHz (26 GHz) and 42.0 – 42.5 GHz



The FCC's 5G FAST Plan

Under Chairman Pai, the FCC is pursuing a comprehensive strategy to Facilitate America's Superiority in 5G Technology (the 5G FAST Plan). The Chairman's strategy includes three key components: (1) pushing more spectrum into the marketplace; (2) updating infrastructure policy; and (3) modernizing outdated regulations.

Spectrum

The FCC is taking action to make additional spectrum available for 5G services.

- *High-band*: The FCC has made auctioning high-band, millimeter-wave spectrum a priority. The FCC will hold its first 5G spectrum auctions this year in the 28 GHz and 24 GHz bands. In 2019, the FCC will auction the upper 37 GHz, 39 GHz, and 47 GHz bands. With these auctions, the FCC will release almost 5 gigahertz of 5G spectrum into the market—more than all other flexible use bands combined. And we are working to free up another 2.75 gigahertz of 5G spectrum in the 26 and 42 GHz bands.
- *Mid-band*: Mid-band spectrum has become a target for 5G buildout given its balanced coverage and capacity characteristics. With our work on the 2.5 GHz, 3.5 GHz, and 3.7-4.2 GHz bands, we could make up to 844 megahertz available for 5G deployments.
- *Low-band*: The FCC is acting to improve use of low-band spectrum (useful for wider coverage) for 5G services, with targeted changes to the 600 MHz, 800 MHz, and 900 MHz bands.
- *Unlicensed*: Recognizing that unlicensed spectrum will be important for 5G, the agency is creating new opportunities for the next generation of Wi-Fi in the 6 GHz and above 95 GHz band.

Infrastructure Policy

The FCC is updating infrastructure policy and encouraging the private sector to invest in 5G networks.

- *Speeding Up Federal Review of Small Cells*: The FCC adopted new rules that will reduce federal regulatory impediments to deploying the small-cell infrastructure needed for 5G (as opposed to large cell towers) and help to expand the reach of 5G for faster, more reliable wireless service.
- *Speeding Up State and Local Review of Small Cells*: The FCC has reformed rules designed decades ago to accommodate small cells. The reforms ban short-sighted municipal roadblocks that have the effect of prohibiting deployment of 5G and give states and localities a reasonable deadline to approve or disapprove small-cell siting applications.

Modernizing Outdated Regulations

The FCC is modernizing outdated regulations to promote 5G backhaul and digital opportunity for all Americans.

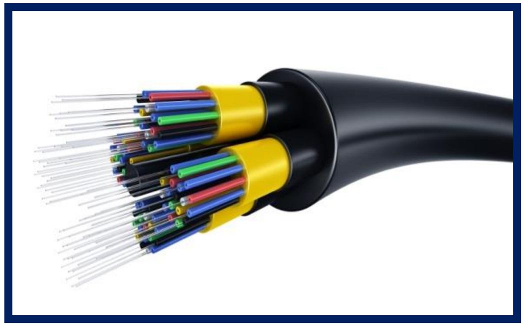
- *Restoring Internet Freedom*: To lead the world in 5G, the United States needs to encourage investment and innovation while protecting Internet openness and freedom. The FCC adopted the *Restoring Internet Freedom Order*, which sets a consistent national policy for Internet providers.
- *One-Touch Make-Ready*: The FCC has updated its rules governing the attachment of new network equipment to utility poles in order to reduce cost and speed up the process for 5G backhaul deployment.
- *Speeding the IP Transition*: The FCC has revised its rules to make it easier for companies to invest in next-generation networks and services instead of the fading networks of the past.
- *Business Data Services*: In order to incentivize investment in modern fiber networks, the FCC updated rules for high-speed, dedicated services by lifting rate regulation where appropriate.
- *Supply Chain Integrity*: The FCC has proposed to prevent taxpayer dollars from being used to purchase equipment or services from companies that pose a national security threat to the integrity of American communications networks or the communications supply chain.

https://docs.fcc.gov/public/attachments/DOC-354326A1.pdf

Spectrum Horizons

- **Proposed to expand access above 95 GHz**
  - **Total of 102.2 GHz to for licensed point-to-point services**
    - 95100 GHz, 102-109.5 GHz, 111.8-114.25 GHz, 122.25-123 GHz, 130-134 GHz, 141-148.5 GHz, 151.5158.5 GHz, 174.5-174.8 GHz, 231.5-232 GHz, and 240-241 GHz band
    - Similar to 70/80/90 GHz rules
    - Licensed nationwide, non-exclusive basis
    - Register links with database manager
    - Seek comment on mobile use
  - **Total of 15.2 GHz for unlicensed use**
    - 122-123 GHz, 244-246 GHz, 174.8-182 GHz and 185-190 GHz bands
    - Similar to 60 GHz rules
    - Selected high absorption bands
  - **New type of experimental licenses > 95 GHz**
    - Longer license terms
    - Ability to sell devices

Much of the spectrum above 95 GHz is allocated for passive services



Achieve Fiber Capacity

Innovations

UNITED STATES PRESIDENTIAL MEMORANDUM

Presidential Memorandum on Developing a Sustainable Spectrum Strategy for America's Future INFRASTRUCTURE & TECHNOLOGY

Issued on: October 25, 2018

- Within 180 days agencies report anticipated future spectrum requirements
- The Director of the Office of Science and Technology Policy (OSTP) shall report on emerging technologies and their expected impact on non-Federal spectrum demand
- The Director of OSTP shall report on recommendations for research and development priorities that advance spectrum access and efficiency
- Within 270 days submit a long-term National Spectrum Strategy that includes legislative, regulatory, or other policy recommendations
- The Chief Technology Officer and the Director of the National Economic Council, or their designees, shall co-chair a Spectrum Strategy Task Force

Spectrum Sharing Today

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Spectrum Sharing Today

- TV White Space (TVWS)
  - US, UK, Canada, Singapore, South Africa, Colombia, numerous other countries worldwide
- Citizens Broadband Radio Service (CBRS)
  - US; possible solution in other countries
- Licensed-Shared Access (LSA)
  - EU—France, Finland, Italy, Netherlands
- Local licensing innovation for sharing, e.g., 1800 MHz, 2.3 GHz, and 3.8-4.2 GHz in UK
- Others, e.g., light licensing, collective use of spectrum and concurrent spectrum access, and of course, sharing in unlicensed spectrum

Spectrum Sharing Today—Spectrum Databases

- Why (Geolocation/spectrum) "databases"?
  - High level of dependability/reliability/certainty required when users access another service's/incumbent's spectrum
  - Allows regulator to keep overall direct/indirect control at all times (e.g., in case of change needed, error or malicious operation, even suspension of framework, etc.)
  - Already prescribed for three bands – TV White Spaces, 3.5 GHz (CBRS Spectrum Access System) and 6 GHz (Automated Frequency Coordination)
- Spectrum sensing
  - Best way to obtain in-situ awareness of the environment
  - Device agnostic
  - New sensing techniques that have detection and characterization built in

Geolocation Database (e. g. Spectrum Access System) and Spectrum Sensing are two tried and trusted mechanisms for sharing

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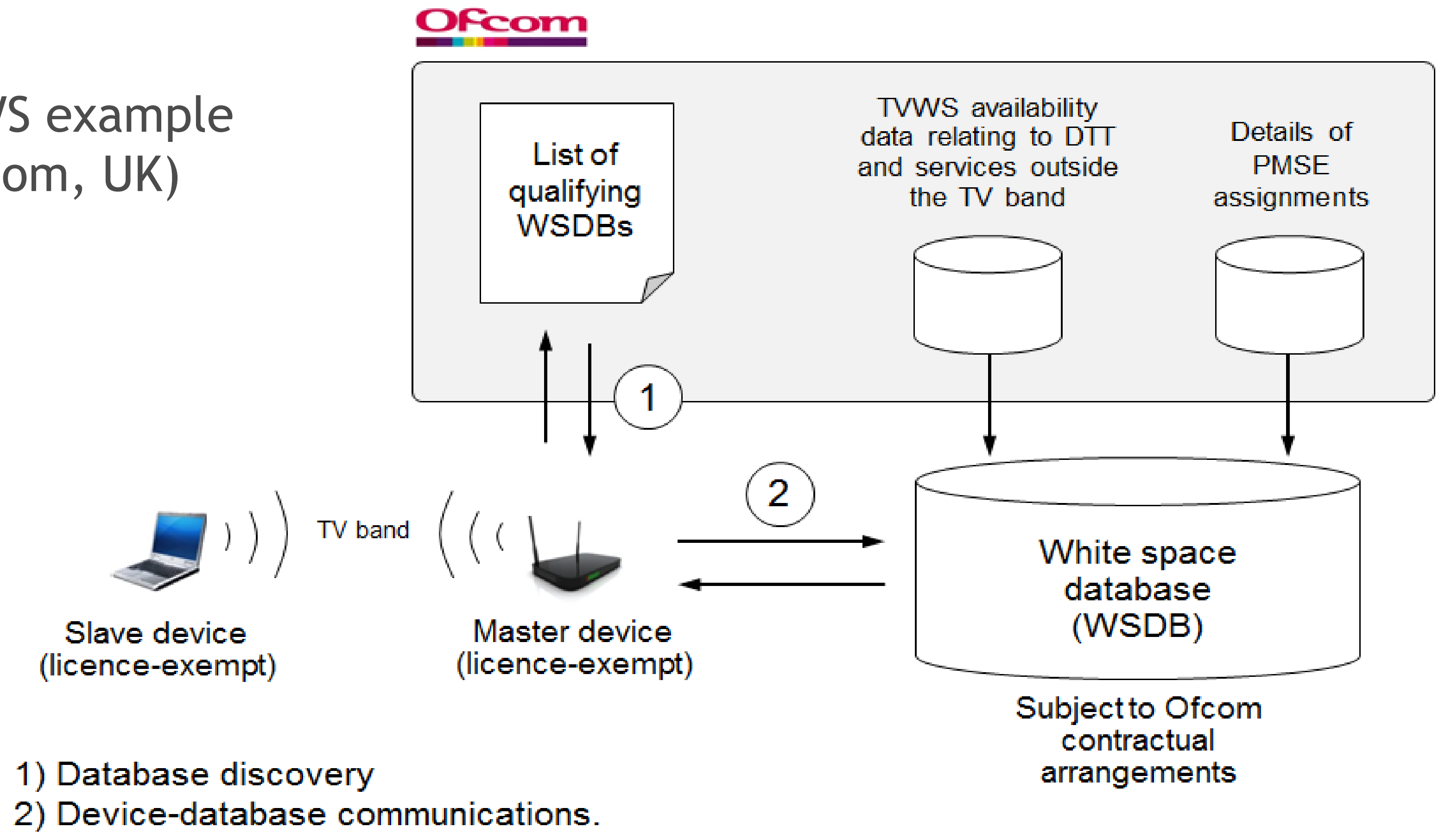
Spectrum Sharing Today—Spectrum Databases

TVWS example (Ofcom, UK)



Citizens Broadband Radio Service (CBRS) is also database (Spectrum Access System) driven

Spectrum Sharing Today—Spectrum Databases

- Can be:
  - License-exempt, e.g., if device entirely automated, integrated GPS (TVWS—UK, CBRS—GAA)
  - Licensed, e.g., if manual configuration of device required (TVWS—UK), local priority-licensed (CBRS—US)
  - Primary-secondary (or even -tertiary) sharing (TVWS, CBRS)
  - Sharing among operators, new entrants, e.g., by agreement of those operators, e.g., with financial compensation (LSA—EU, France, Finland, Italy, Netherlands)
  - Device (TVWS, CBRS) or network (LSA, CBRS) interacting with the database
  - Manual ("Enabling Opportunities for Innovation"—UK, various light licensing approaches, etc.), or automated

Various Regulatory Regimes for Spectrum Sharing

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Spectrum Sharing Today—Spectrum Sensing

- Energy detection
- Feature detection, e.g.,
  - Cyclic prefix
  - Autocorrelation
  - Cyclostationary

Detection hypothesis

$$H_0: \quad y(k) = w(k) \qquad \text{signal absent}$$

$$H_1: \quad y(k) = w(k) + s(k) \qquad \text{signal present}$$

$$z = z(y(1), y(2), \ldots, y(N)) \qquad \text{test statistic}$$

$$\text{if } z > \zeta \text{ then } H_1$$

$$\text{else } H_0$$

$$\zeta: \quad \text{sensing threshold}$$

Probability of detection

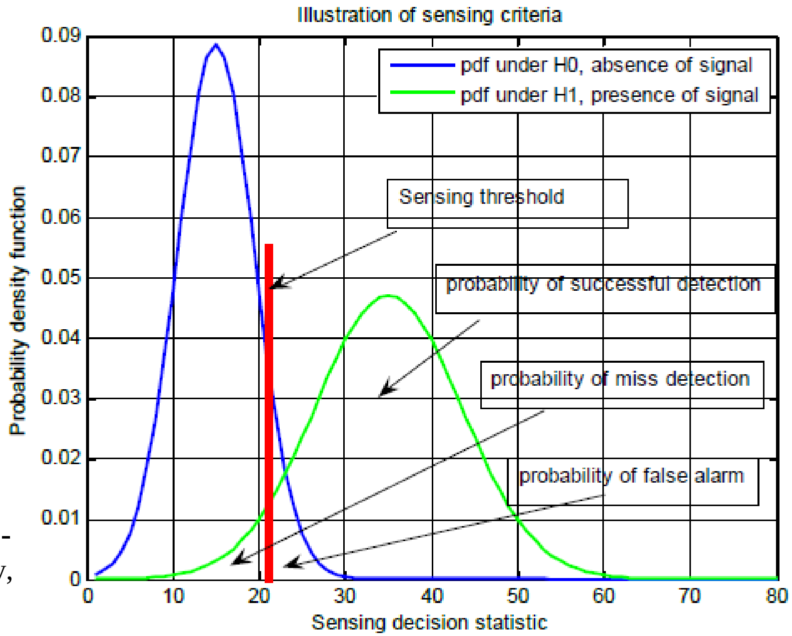
$$PD = prob(H_1 \mid H_1)$$

Probability of mis-detection

$$PMD = prob(H_0 \mid H_1) = 1 - PD$$

Probability of false alarm

$$PFA = prob(H_1 \mid H_0)$$



Partially adapted from content presented in O. Holland, M. Nekovee, “Spectrum Awareness”, ICT-ACROPOLIS Summer School 2011, Florence, Italy, June 2011

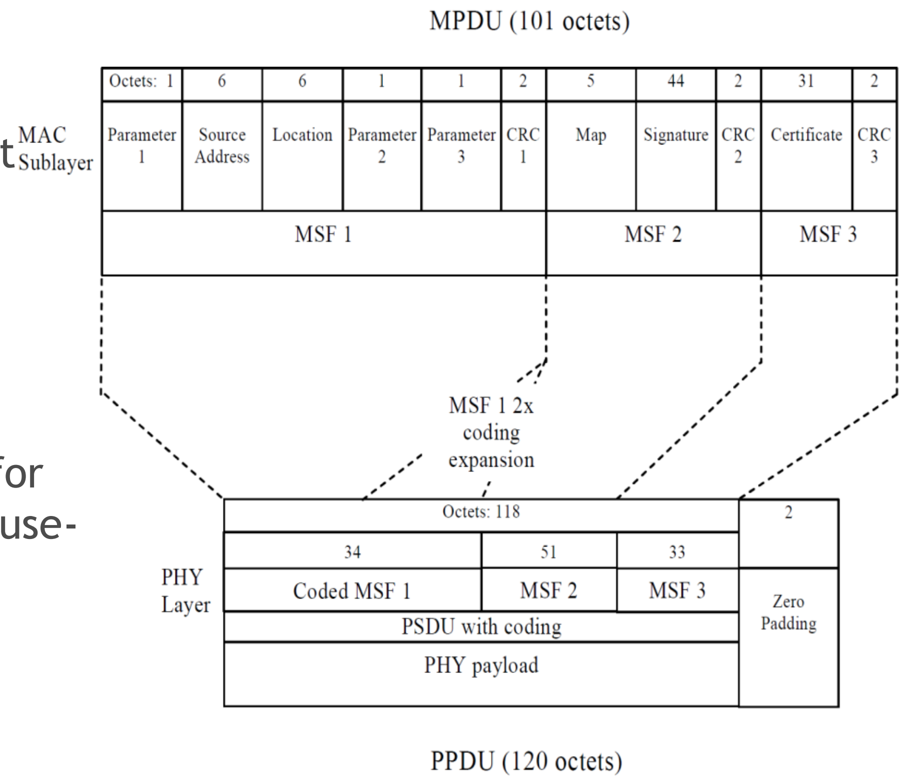
Spectrum Sharing Today—Spectrum Sensing

- Still is (or can be) used in some cases
  - Environmental Sensing Capability (ESC)
  - Very low-power white space devices in US
  - Coordination among license-exempt devices
  - 5 GHz
- Of course, can greatly assist regulatory processes
  - E.g., interference potential/interferer detection, spectrum forensics
  - Understanding of the spectral situation, e.g., to assess potential for sharing gains

Sensing as in Environmental Sensing Capability (ESC) has been already adopted in the 3.5 GHz Band. 5G Eco-system is involved in adopting it.

Spectrum Sharing Today—Beacons

- One of the best techniques for avoiding the hidden node issue
- Beacons is one of the few options to protect Primary User that is Passive (e. g. Satellite Receiver Stations)
- Beacons are also very good for Dynamic Coordinated Spectrum Sharing
- Beacons can be designed for robustness or for fast information transfer depending on the use-case.



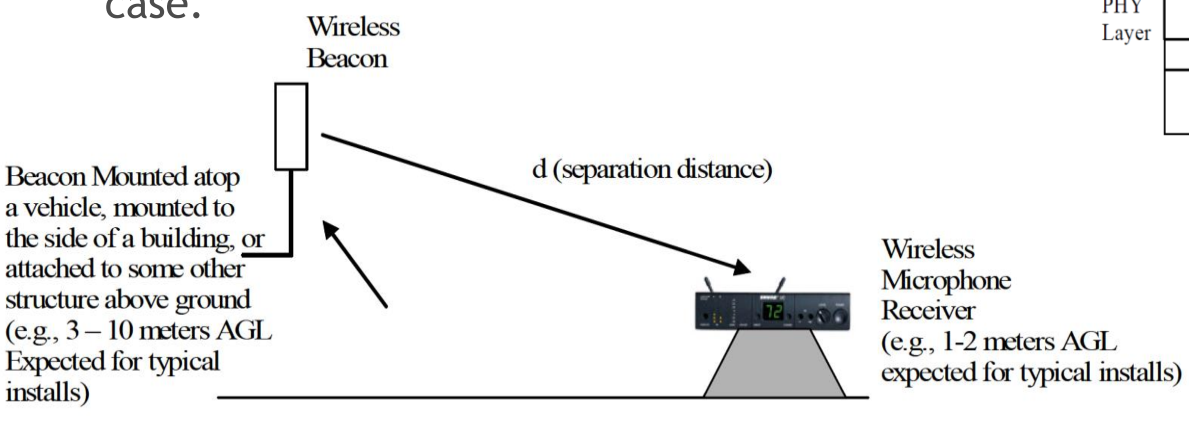


Figure B.1—Beacon/wireless system separation distance

Beacons is one of the few options to protect Primary User that is Passive (e. g. Satellite Receiver Stations)

Spectrum Sharing Insights

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Federal / Non-Federal Sharing

- **Presidential Jun 2010 Memorandum (calling on FCC & NTIA) to make 500 MHz of Federal & Non-Federal Spectrum available for commercial wireless by 2020.**

- NTIA Fast Track Rpt. 2010 identifying 1st set of Federal Spectrum to be re-purposed
- AWS-3 SPECTRUM AUCTION (1695-1710, 1755-1780, 2155-2180 MHz)
- 3.5 GHz CBRS (3550-3700 MHz)

Primary System to be protected: Federal licensed incumbent
Secondary System: New (either un-licensed or licensed with lower priority than incumbent)

AWS-3 (1695-1710, 1755-1780)

- 38+ systems/capabilities affected by the AWS-3 transition → must **relocate to another DoD band**, **compress into**, or **stay & retrofit (share spectrum)**

- **US Govt. will modify selected systems to operate at both 1780- 1850 MHz and 2025-2110 MHz**
  - Small Unmanned Aerial Systems
  - Tactical Targeting Network Technology
  - Tactical Radio Relay
  - High Resolution Video
- **US Govt. systems will remain in the 1755-1780 MHz band and share spectrum with commercial users as follows**
  - Satellite Operations at 25 locations
  - Electronic Warfare
  - Air Combat Training System
  - Joint Tactical Radio System (6 sites)
- **US Govt. will compress the remaining 1755-1780 MHz operations into 1780 - 1850 MHz**
  - Air Combat Training System
  - Joint Tactical Radio System at all other sites
  - Precision Guided Munitions
  - Aeronautical Mobile Telemetry

3GPP Eco-system is heavily involved in enabling spectrum sharing in these bands

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Operational Approaches to Spectrum Sharing

- **Non-collaborative** (no information exchanged at operational time)
  - Easier (retro-fitting, particularly on secondary with no requirements on primary (Federal system)
- **Collaborative** (side channel for info exchange at operation time/scale)
  - Knowledge of incumbent parameters (pulse duration/burst length, beam pattern, angular rotation speed) *can potentially reduce exclusion regions*
  - Encourage new **interference tolerance** approaches for primary

There are regulatory use-cases for both Non-collaborative and Collaborative Sharing

EXCLUSION REGION (3.5 GHz): Ship Borne Radar

Figure B-1. Shipborne Radar 1–exclusion zone lower 48 states (yellow line–fast track exclusion zone and blue line–revised exclusion zone).

NTIA Rpt. 15-517 Jun 2015 (Exclusion Zone Analyses & Methodology:

Highlights impact of Model Assumptions !

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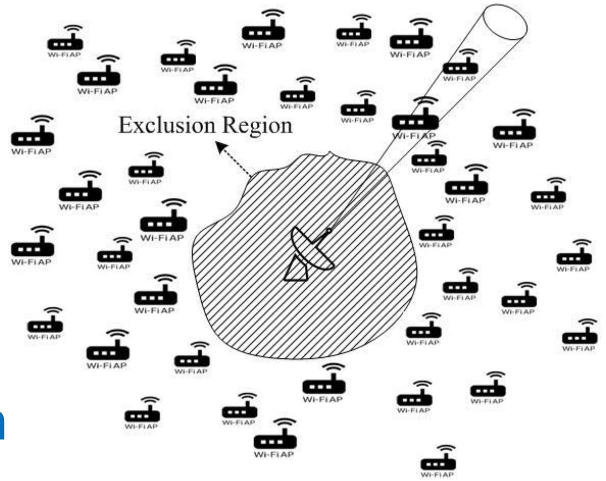
Incumbent Protection

EXCLUSION & PROTECTION REGIONS

- **Exclusion Zone**: A region around the primary with no co-channel active secondary txmission
- **Protection Zone**: A region with active secondary txmitters, but with constraints so as stay within `acceptable interference' limits
- **Design Objective: minimize exclusion region subject to protection of primary.**



Exclusion Region depends on multiple factors: sensitivity of victim receiver, interference margin, secondary txmit power, path loss model

Incumbent Licensee: 'primary' (to be protected from interference)
New User: `secondary' (no interference protection)

Effective Sharing can be Staged to be Successful

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Spectrum Sharing Tomorrow

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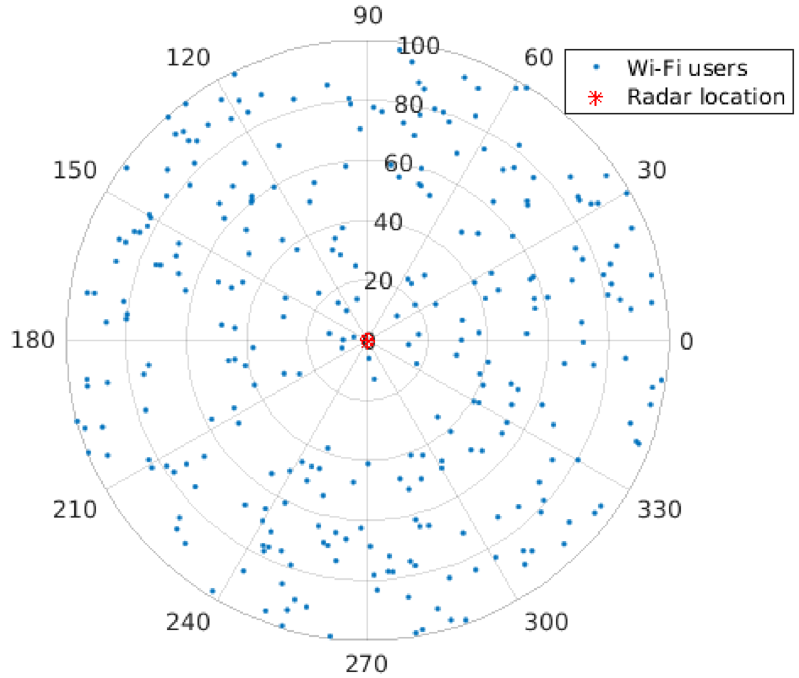
Example: Radar-IEEE 802.11 Coexistence

Homogeneous Poisson Process Deployment



$$P(\Phi(A)=n)=\frac{(\lambda_{AP}|A|)^n}{n!}e^{-\lambda_{AP}|A|}$$

$$I_{aggr}=\sum_{\mathbf{x}\in\Phi}\frac{P_{su}G(\theta_{\mathbf{x}})}{\text{FDR}(\Delta f)}l(||\mathbf{x}||)$$

$$l(r)=r^{-\alpha}$$

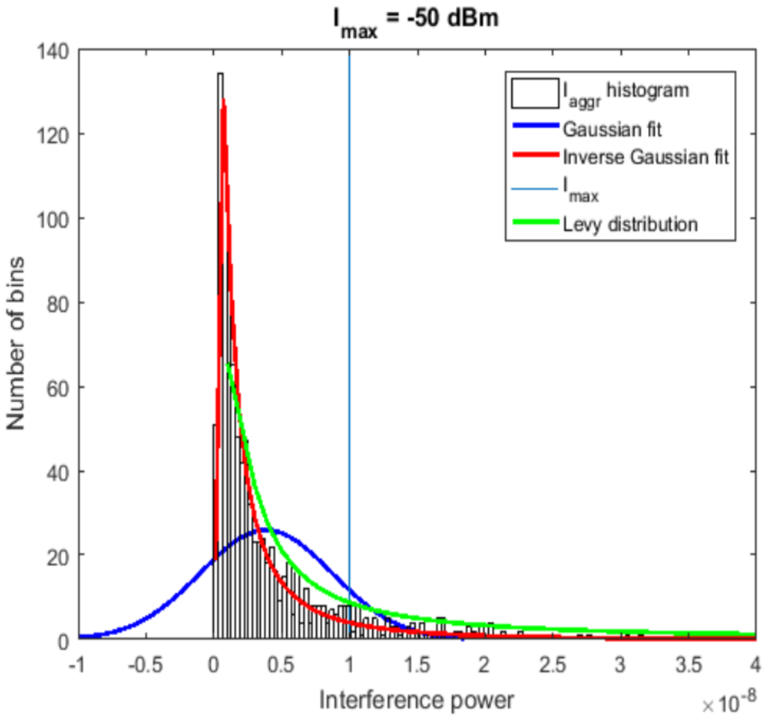
***α* = 4 → closed form expression**

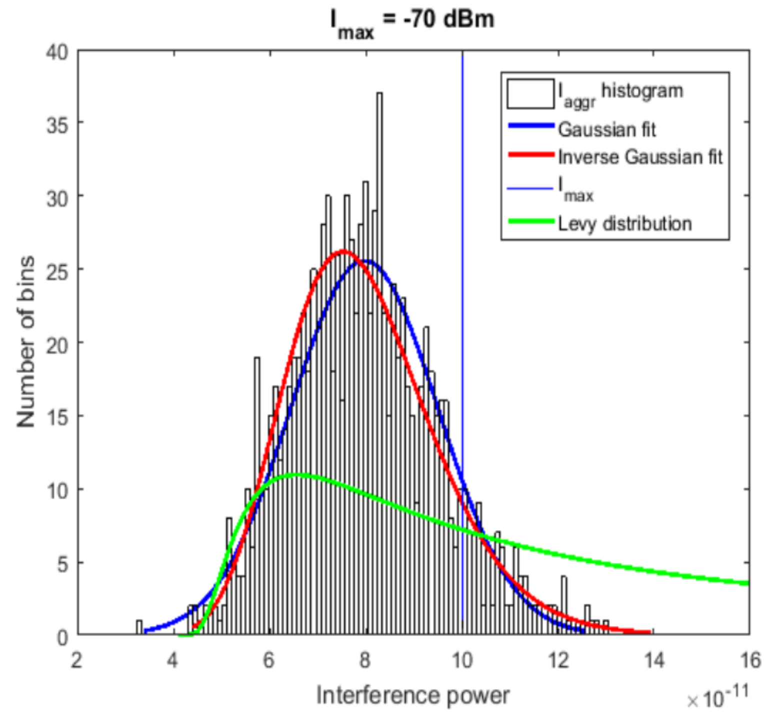
$$f_{I_{aggr}}(x)=\frac{\pi\lambda}{2x^{3/2}}exp\left(-\frac{\pi^3\lambda^2}{4x}\right)$$

Levy distribution

Aggregate interference presented by the incumbent is often Non-Gaussian – Hence requires new methods

Distribution of I_{aggr} with Protection region





- **Gaussian Approximation – works lower aggregate Interference (large protection regions)**
- Otherwise significantly Non-Gaussian

Aggregate interference presented by the incumbent is often Non-Gaussian – Hence requires new methods

Incumbent Protection vs Incentivizing Secondary

- Radar protection from IEEE 802.11:

  → sensing by IEEE 802.11 nodes + Dynamic Frequency Selection (DFS)

  - sensing by IEEE 802.11 for radar incurs some cost (IEEE 802.11 throughput degradation) !

    e.g. insert quiet periods in IEEE 802.11 to listen/detect radar

Good Design → Acceptable Trade-offs
satisfy radar protection requirements while minimizing
IEEE 802.11 throughput loss (latter has been often neglected)

Detection – Search Radar

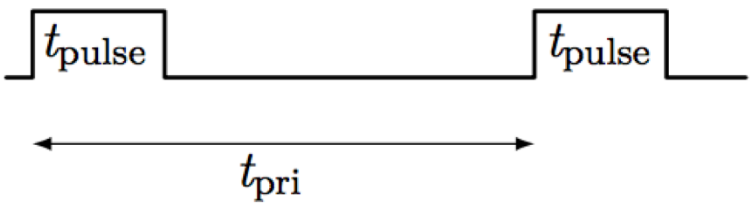
Spatio-temporally varying use of Spectrum Resources

Radar rotates in azimuth with angular rotation speed (e.g. once in few sec)

At any location: emits a burst of pulses →

a) pulse duration (e.g.1 μs)

b) b) pulse repetition interval (10 μs)

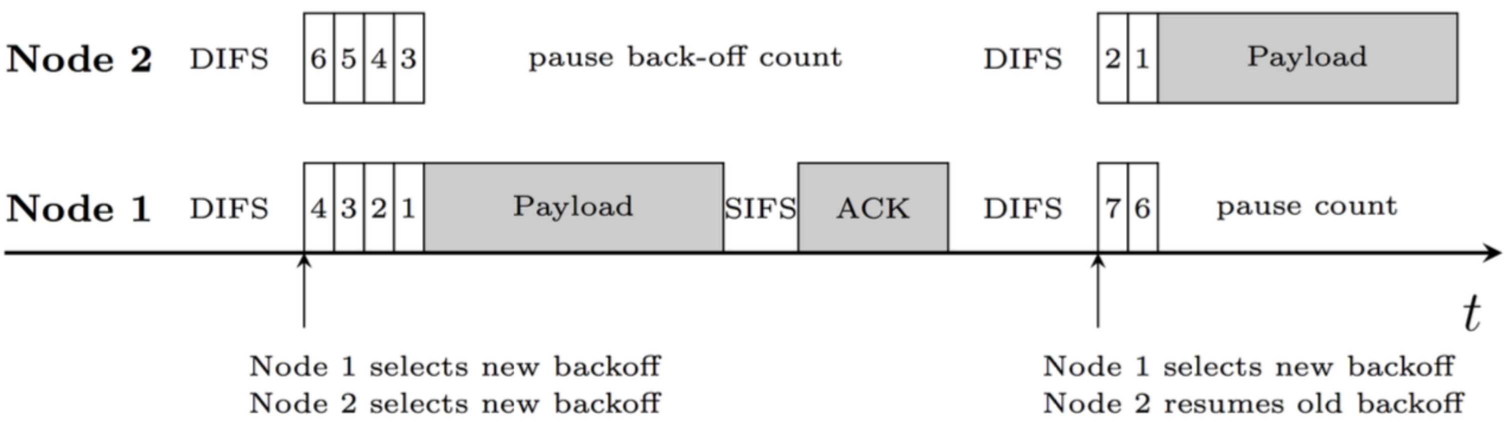


A pulse burst

Example of balancing incumbent protection with secondary enablement

IEEE 802.11 MAC: CSMA/CA

Nodes use Carrier Sensing Followed by Random Back-Off



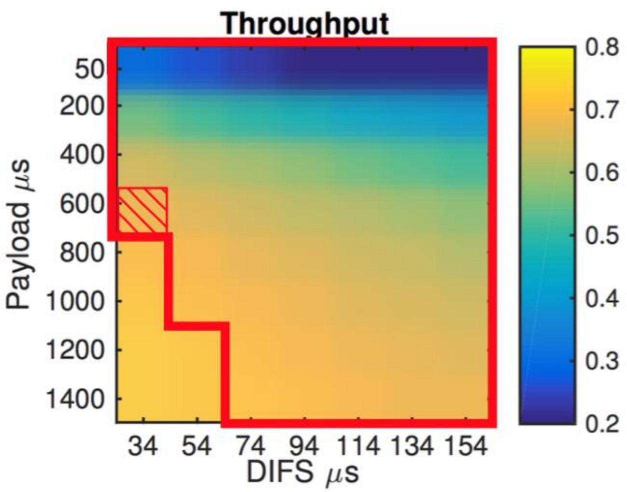
t_{slot}	t_{bo}	t_{difs}	t_{sifs}	t_{ack}	t_{payload}
$1\mu s$	$9 \times t_{\text{slot}}$	$34 \times t_{\text{slot}}$	$16 \times t_{\text{slot}}$	$48 \times t_{\text{slot}}$	up to $\approx 3000 \times t_{\text{slot}}$

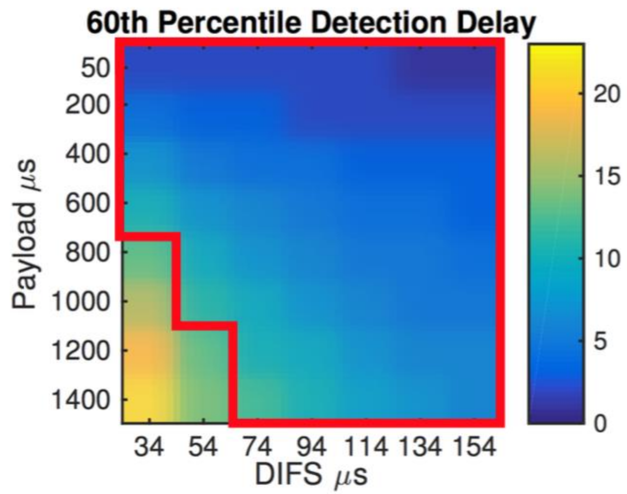
Quiet Periods in IEEE 802.11 (all nodes backed off)

Throughput vs Detection Trade Off

IEEE 802.11 Knobs: Payload Size & DIFS duration

- Increased DIFS → more quiet periods ⇒ better detection, lower throughput
- Increased Payload → higher throughput



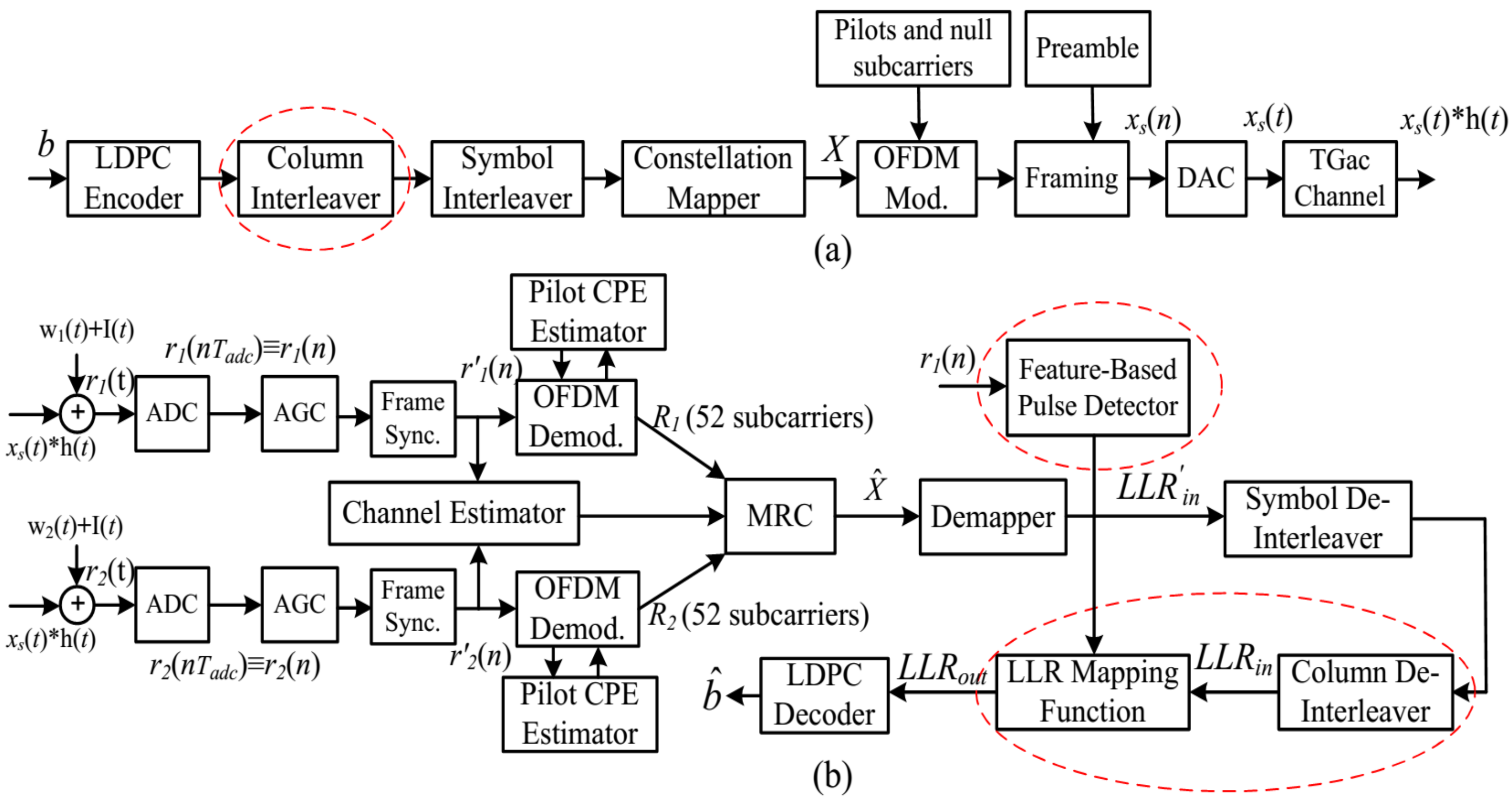


PRI	$250\mu s$	$1429\mu s$	$5000\mu s$
Pulse Duration	$1\mu s$	$1\mu s$	$5\mu s$
d_{burst}	25	18	10
Target Burst P_d		0.6	
Clients		10	
Max Throughput	0.7363	0.715	0.6470
Payload Duration	$1.5ms$	$930\mu s$	$400\mu s$

Example of balancing incumbent protection with secondary enablement

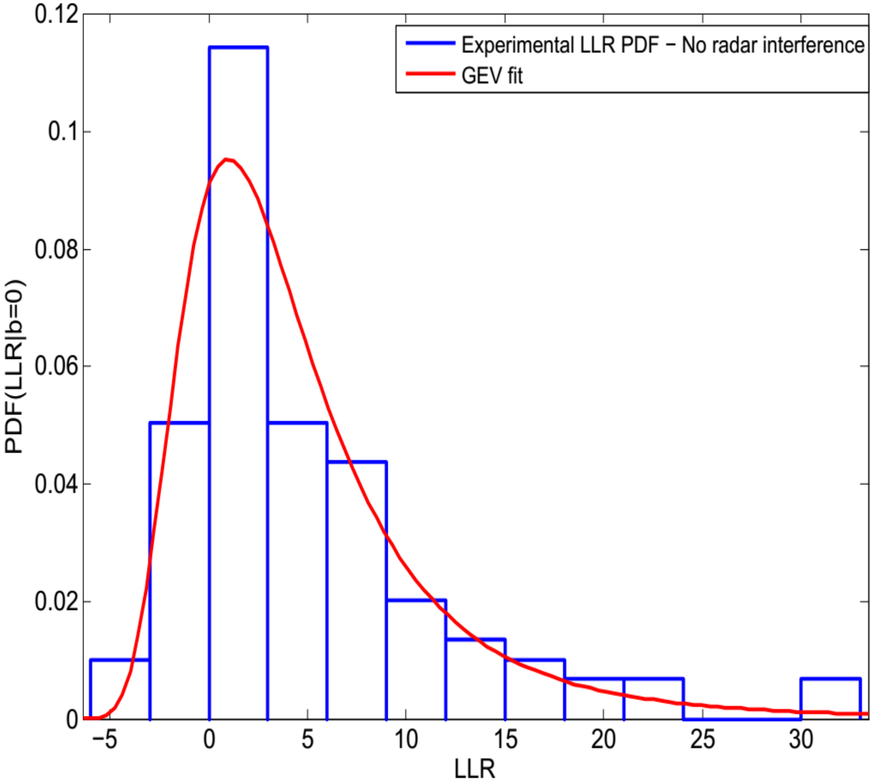
Robustifying IEEE 802.11 to Pulsed Radar

➢ The circle boxes illustrate the elements added to the modified IEEE 802.11 system.

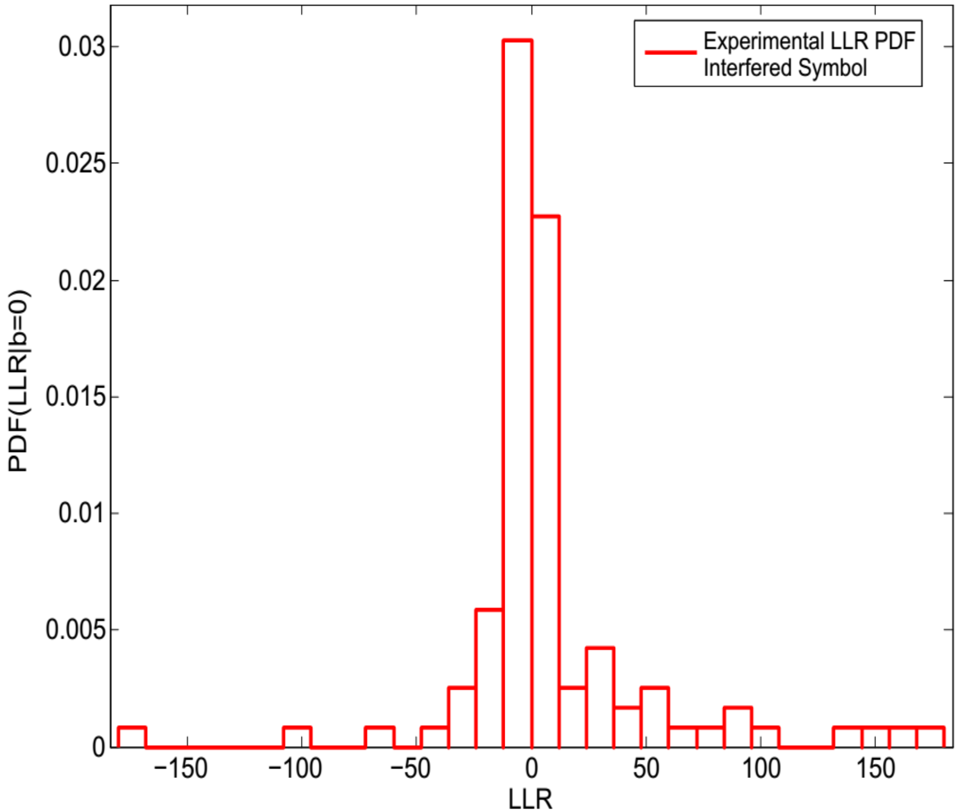


Histogram at decoder input

- No radar interference histogram follows a Generalized Exponential distribution
- Radar interference histogram has a very large magnitude with zero mean and large variance.



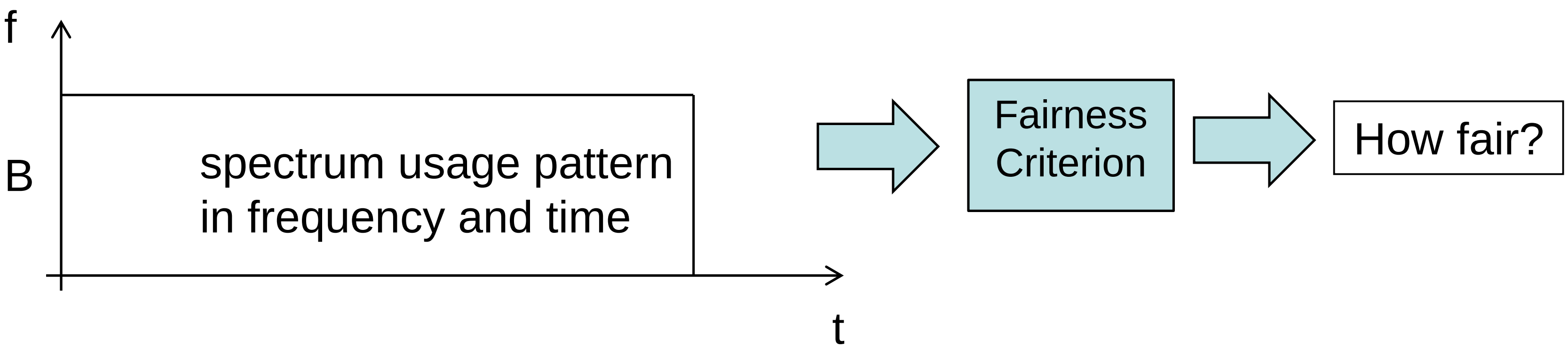
(a) No radar interference



(b) Radar interference

Fair Spectrum Sharing

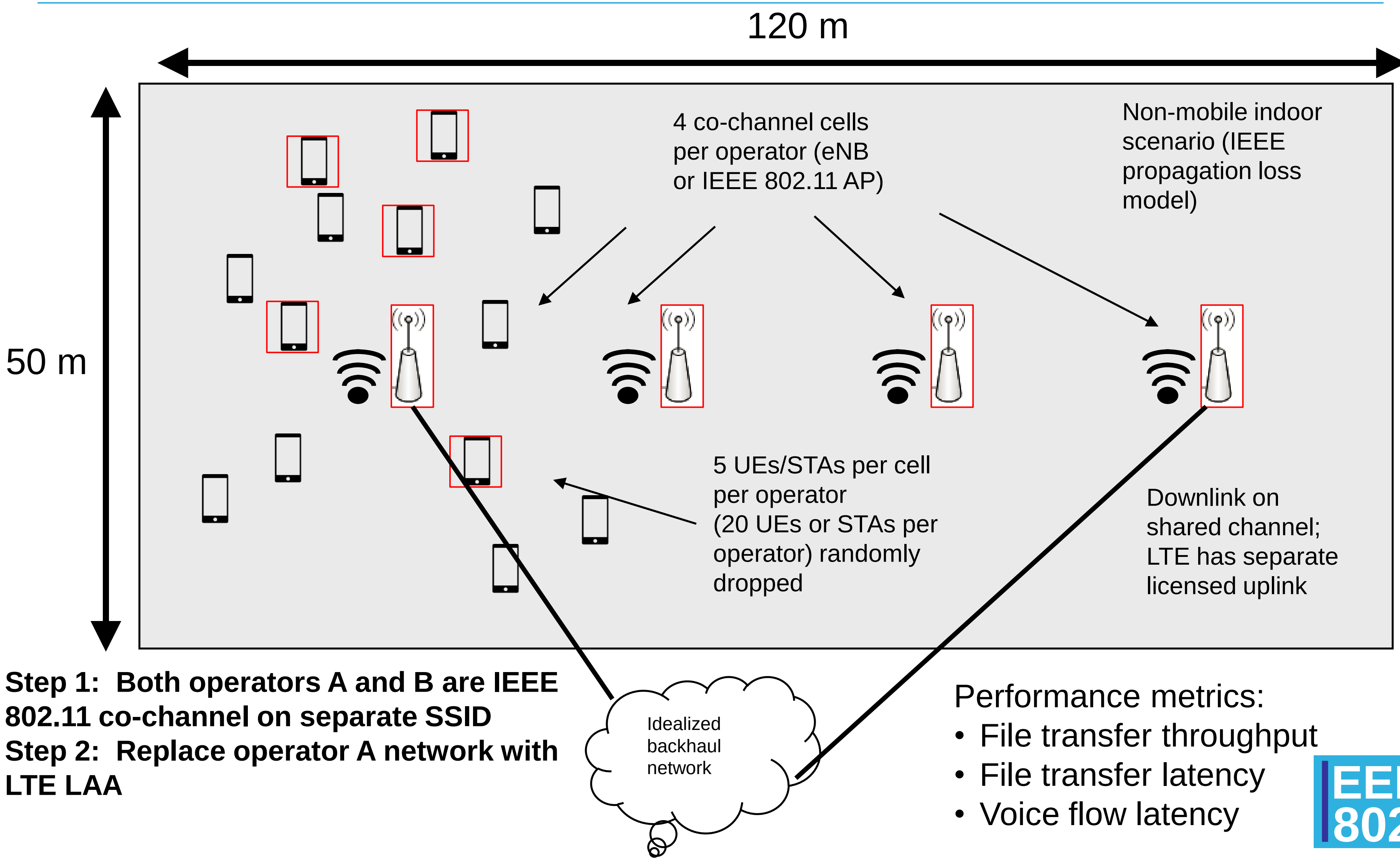
- Should define a criterion that takes as input a given instance of spectrum usage pattern of the systems or users in the shared spectrum and delivers as output a measure of fairness for this instance of spectrum sharing (802.19-14)



- Spectrum usage is highly impacted by the access protocol used by each system
  - The fairness criterion should be defined in terms of ***accepted network QoS parameters (throughput, time share, access…)***

In a Fair frame-work, everyone brings out their best techniques

Example: LTE-LAA/IEEE 802.11 Fair Sharing 3GPP



Step 1: Both operators A and B are IEEE 802.11 co-channel on separate SSID
Step 2: Replace operator A network with LTE LAA

Performance metrics:

- File transfer throughput
- File transfer latency
- Voice flow latency

LTE-LAA /IEEE 802.11 Fair Coexistence: Comments

- ➢ Multiple categories (Cat 1-4) of LTE-LAA, behave very diff. with IEEE 802.11
- ➢ Even for Cat 4 (most DCF like LTE-LAA)

  Impact of LTE-LAA → IEEE 802.11 and IEEE 802.11 → LTE-LAA asymmetric

- ❖ By tuning of resp. ED thresholds (IEEE 802.11 and LTE-LAA), TXOP (LTE -LAA), per-user t'put of the resp. networks can be changed favorably!

Time Fairness does not equal Throughput Fairness!

M. Mehrnoush et al ``On Fairness of IEEE 802.11 & LTE-LAA Coexistence"

Near term Technologies wireless/5G Spectrum Sharing

Numerous technologies across wireless (and fixed) exist to support future spectrums Sharing:

(1) Advances in RAN capabilities
(2) Multi-user MIMO
(3) Beamforming
(4) Network controllers
(5) Software Defined Networking
(6) Network Functions Virtualization
(7) Location Data Base for Unlicensed/Shared spectrum
(8) Geo-location specific Devices

Many of these are already being used to some degree in today's networks and initial 5G NR deployments -- ***In the future low latency, efficiency, and SLAs for a range of end-user requirements, will matter as much as bandwidth***

Technology primitives underlying new deployments

Advancing Spectrum Sharing Techniques

(1) Dynamic Spectrum at the RAN in coordination with Slicing requirements
- New Radio Access techniques
- Massive MIMO with spatial awareness/adaptive beamforming
- Device to Device (D2D) control with high mobility – eMBB

(2) And Network Slicing, supported at the core/RAN by:
- a wireless software-defined network,
- network function virtualization,
- Separate of control/data planes and new orchestration functions

Supporting Maximum Efficient use of Spectrum Sharing for:
- network ultra-densification,
- **Edge Computing**
- big data and mobile cloud computing,
- scalable Internet of Things

Looking forward to 5G Release 17

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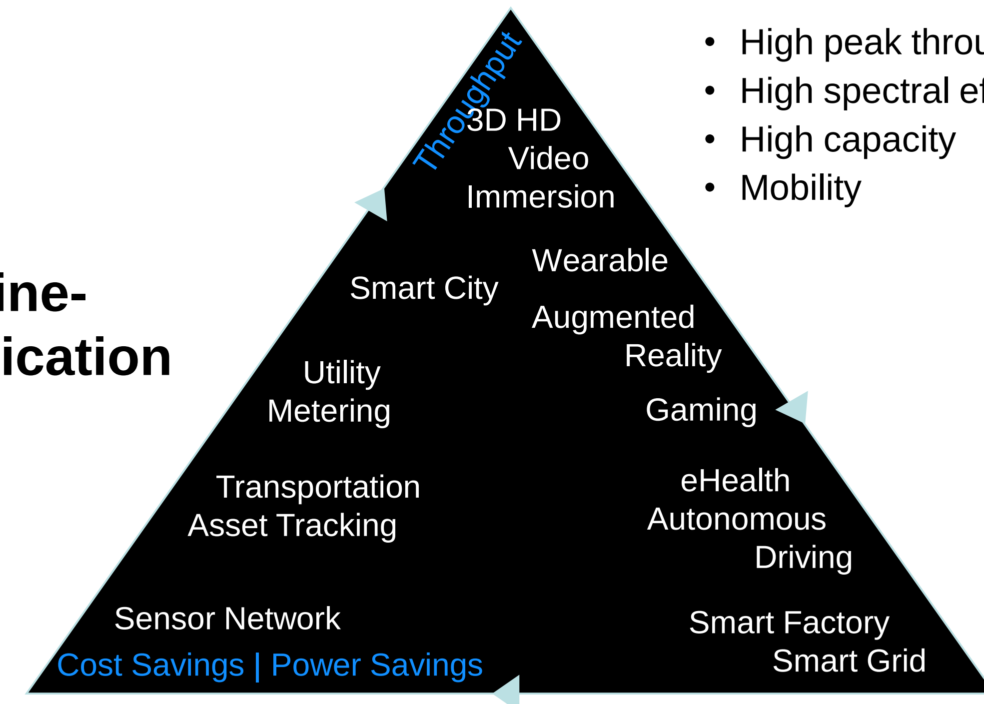
Emerging Technologies Must Support Disparate Needs

Enhanced Mobile Broadband (eMBB)

- High peak throughput
- High spectral efficiency
- High capacity
- Mobility



Massive Machine-Type Communication (mMTC)

- Network and device energy efficiency
- Massive number of connections
- Very large coverage

Ultra-Reliable Low Latency Communication (URLLC)

- Ultra-high reliability
- Ultra-low latency

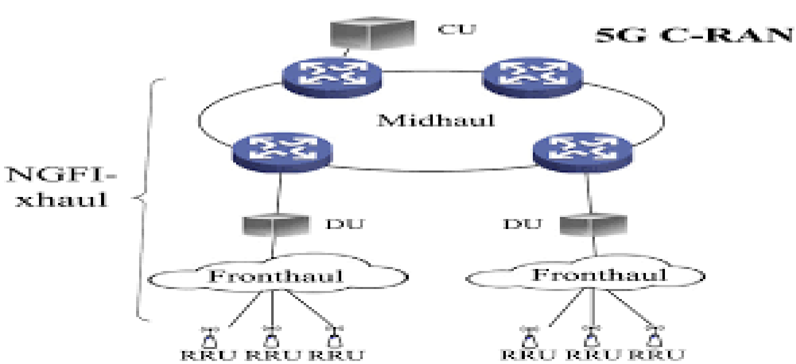
From: Dark As Dark Can, The Untold Keynote – May 2015, Sabine Roessel, Intel Corporation

mMTC and URLLC are the new kids on the block in 5G

New requirements for the RAN architecture

<u>Radio Front-end</u>

- **Scalable OFDM** – use “sub slots to enhance flexibility and latency which supports:
- **Shortened TTI** – reduces latency
- **Massive MIMO** – large numbers of bearers (hundreds) to increase bandwidth in sub-6GHz bands integrated with:
- **Spatial Adaptive Beam Forming** – extends range/cell size



Semanticscholars.org

Source inpart: Samsung 5G

<u>RAN innovations/new complexities</u>

- **vRAN –** Virtualizing the BBU
- **Versus** C-RAN (cloud/centralized RAN – with “Front Hauling” to BBU
- **CoMP** – coordinate muUE attached to multiple cells to provide greater reliability (Qualcomm)
- **Deployment:** Dense cell
- **Decoupling traditional management functions (i.e., seesion-mobility)**
- **Peer to Peer** (Device to Device – D2D) provisioning
- **Edge/End-point slicing/computing –** SWAP and complexity trade-offs
- **Cross Domain management**

Reconfiguration of the Core vs the Edge

End-to-End Dynamic Network Slicing

Aligning with Network functions and multiple end user requirements to optimize end-to-end Service Level Agreements (SLA) from Core to RAN and End Device

- **Core Leverages:** NFV (Network Functions Virtualization & SDN (Software Defined Networking) techniques, Cross Domain Orchestration, and related “Awareness” concepts

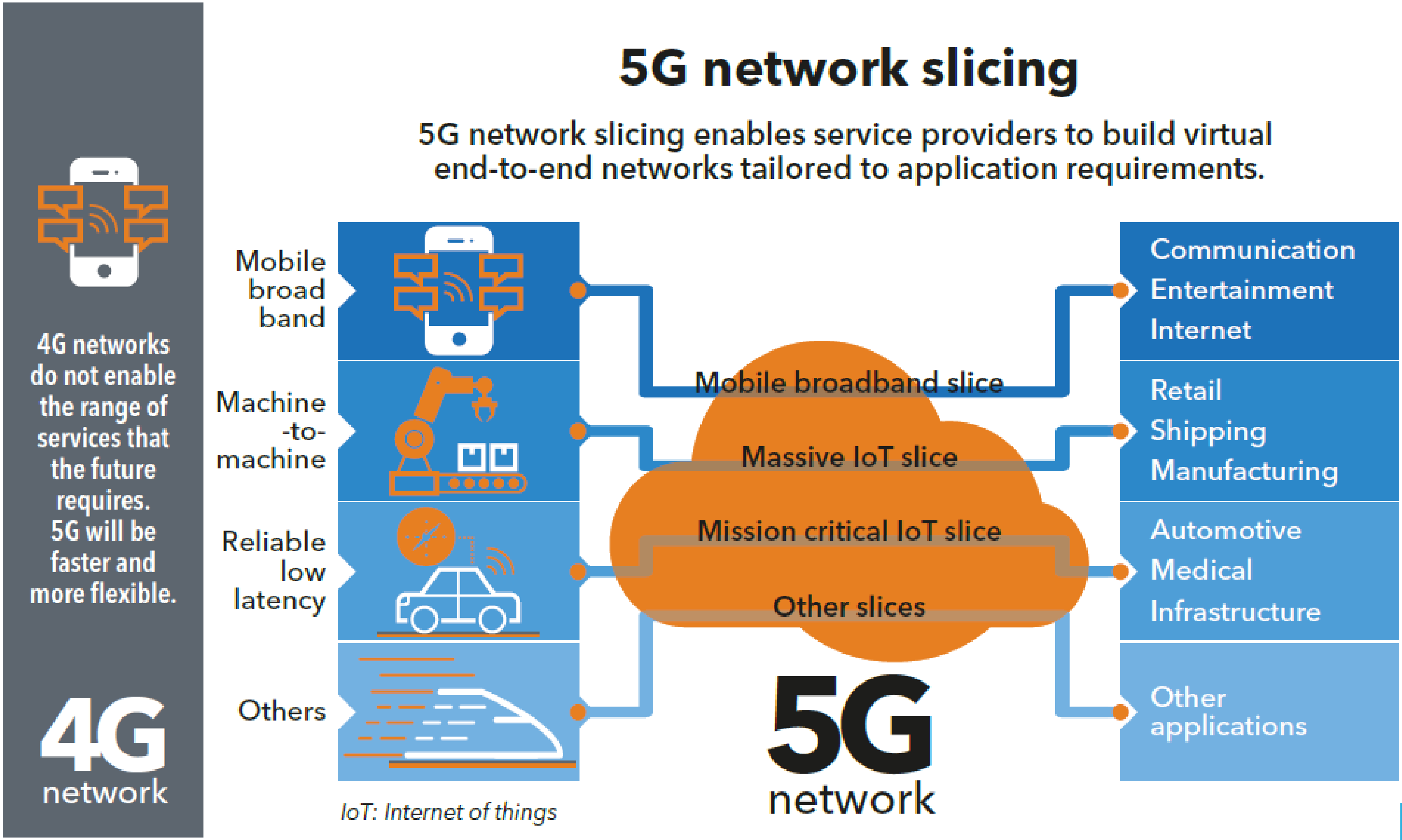
- **RAN:** Use hardware radio resources and spectrum, with technologies/concepts to include: Edge computing, Flexible NR front-end, massive MIMO, low-latency (sub frame for <1ms), etc

Key End-User requirements:

- low latency and high reliability
- massive connection
- high spectrum efficiency
- high data rate
- Distributed & wide coverage

Networked Virtualization needs to happen end to end – Core as well as RAN

5G Slicing – Multiple Use Cases



Source: https://news.itu.int/why-end-to-end-network-slicing-will-be-important-for-5g

Questions & Opportunities for End-to-End Network Slicing

- Implement so that the network control is agnostic to each vertical use (i.e. V2I – V2V, massive IoT, VR, etc
- Initial RAN slicing has been show to improve performance and resource allocations for the user – can base stations handle the added complexity
- Spectrum re-use, especially at the higher bands, is a big opportunity
- Service Provider (SP) spectrum slices: how many & customer control?
- Slice hand-offs: how to connect to other SPs slices? How to connect to a Multiple System Operator Slice? (i.e., integrate with cable providers and for MEACs)
- Policy concern on Slicing QoS: Potential legal avenue around Net Neutrality?
- User management options – addressing complexity and autonomous of multiple varying Slices with AI implementation?
- Slicing standards and final definition are still ongoing (scheduled for Rel 17 2020)

What is IEEE 802' s Approach to Network Virtualization?
These are the hard problems at the core of 5G Utopia …

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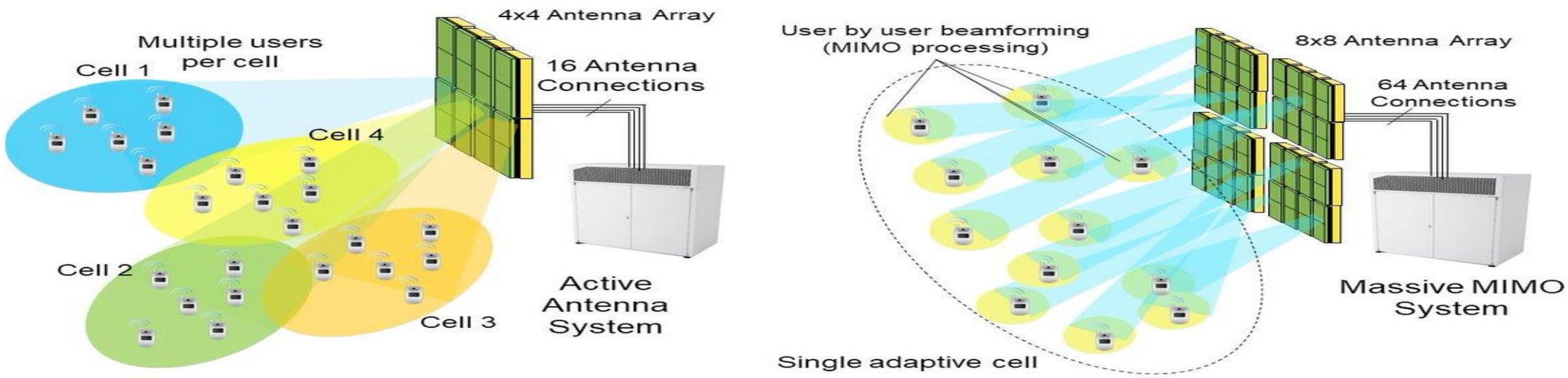
Massive MIMO Concept and Needs

- mmW – above 10 GHz, reflection/scattering will be the key for NLOS propagation
- Basestations at this frequency and higher would need to be inbuilding
- Antenna in array exceeds users; adding high gain adaptive beamforming toc increase coverage and minimize interference; Use with Spatial and Time Domain controls to maximize Spectral Reuse
- Evolving research with AI/ML techniques to add/enhance blind source identification, direction finding, etc.



Spatial Adaptive Beamforming with Massive MIMO is corner-stone of the 5G Spectrum Re-use …. One of the Utopia

https://www.edn.com/electronics-blogs/5g-waves/4459761/Realizing-5G-New-Radio-massive-MIMO-systems; January 8, 2018

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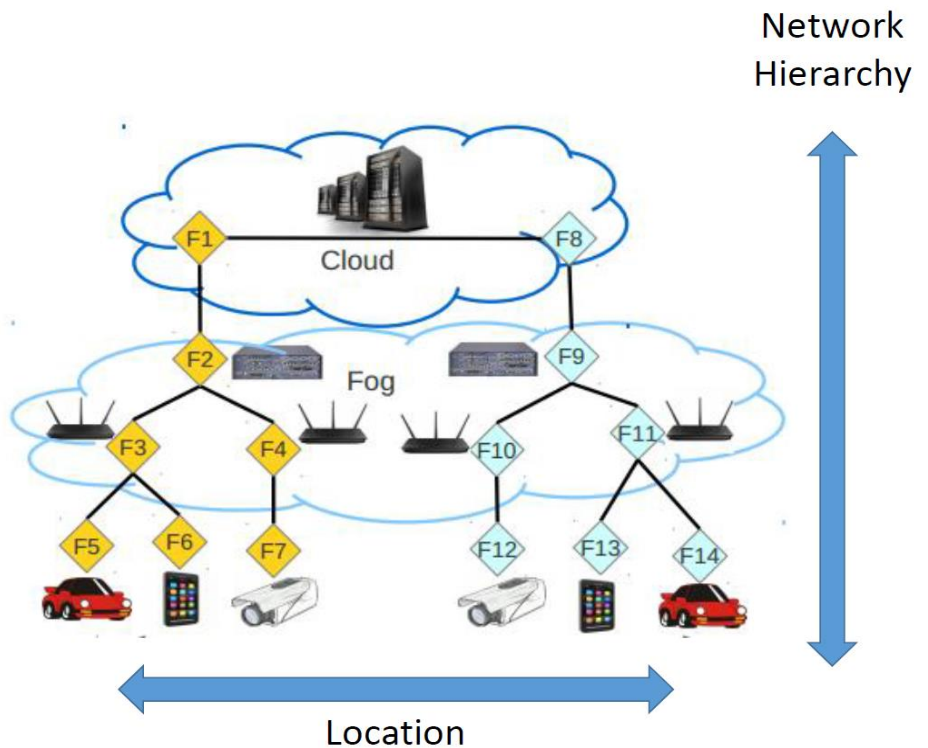
Multi-access Edge control – The Best of Both Worlds

Edge Computing (akin to FOG – a superset) allows different parts of the system to maximize their strengths

- Cloud
  - Massive storage
  - Heavy computation
  - Global coordination
  - Wide-area connectivity
- Edge/Fog
  - Real-time processing
  - Rapid innovation
  - Client-centric
  - Edge resource pooling
- Issues
  - More complex and power-hungry edge devices
  - Parsing of data – efficiency vs. loss of context



RAN to the Mobile Edge and back to the Core

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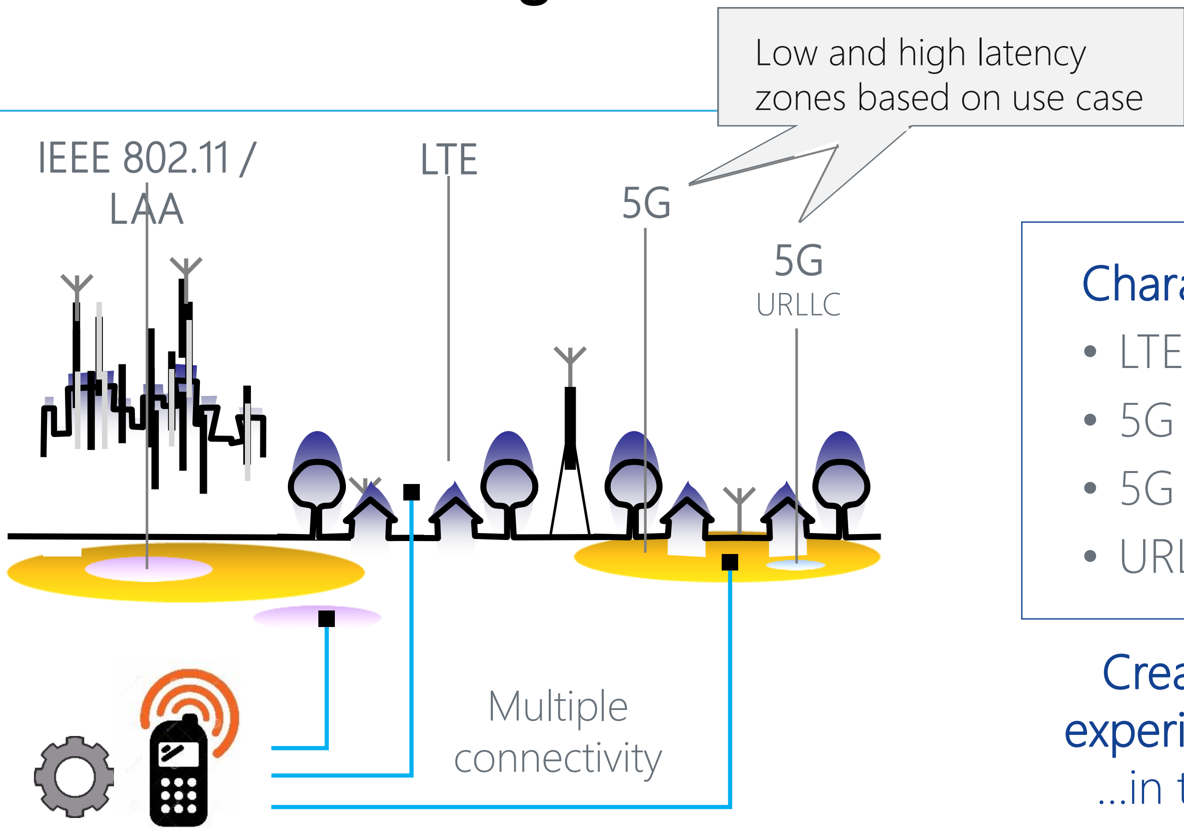
Agnostic but Smart MEC



Characteristics
- LTE WAN baseline
- 5G low & mid band WAN
- 5G mmWave Hot Spots
- URLLC Hotter Spots

Creating a seamless user experience will be important
...in throughput & latency

Smart Edge Computing is Increasingly Necessary for ALL Networked Systems

- Edge computing is feasible (required) for high bandwidth, connectivity afforded by 5G and App demands.
- Spans the enterprise data enter, the WAN, the cloud, and the Edge
- SWAP constraints – need hybrid with functions at the edge

* Contribution from Nokia

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New Technologies that are Needed

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Emerging Technology: Beyond the Networks

"DATA is the new OIL" (Kyle Conner, Cisco)

- Integration of AI for dense, dynamic end user requirements
- Machine Learning (Can machines teach machines functions?)
- Mobility as a Service will be a feature
- Virtualized devices
- Atomic clock chips – geo-location
- Connections and Service Level Agreements (SLA's) automated with SDN/NFV, Context Aware = AI
- 3D-Ultra-Massive MIMO at Terra Hz……

Smart Edge Computing is Increasingly Necessary for ALL Networked Systems

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New Technologies and Standards to make this happen

- Technologies that assist in improved electromagnetic spectrum awareness, sharing and use
- Spectrally efficient communications technologies
- New bi-directional spectrum sharing policies
- Spectrum Sharing Tools – Spectrum Access Systems, Sensing and Beaconing Techniques
- Understanding Federal Systems – e. g. Radars, SATCOM that need protection
- New interference mitigation technologies
- Optical links that can off-load high-capacity point to point traffic
- Networked Slicing
- Security, trusted micro-electronics and computing
- Co-existence analysis, Interference Assessment and Monitoring
- Full-Duplex and Simultaneous Transmit and Receive,
- Spectrum sharing in new frontiers – mmWave and Terra Hz

New Architectures, New Policies, New Technologies and New Signal Processing

Why IEEE 802 Community Needs to be Involved and Follow-on Actions

Apurva N. Mody, National Spectrum Consortium
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Why IEEE 802 should look into this and Next Steps

- Licensed eco-system is already looking into this. AWS-1 and AWS-3 spectrum will result in bi-directional spectrum sharing between LTE networks and Federal systems
- IEEE 802 has always thrived on disruption.
- We need a new disruptive paradigm and policy whose time has come …

Next Steps

- Set up an Executive Committee Study Group to look at Spectrum Sharing needs arising from various regulations for various spectrum bands.
- Identify the mechanisms that will be needed (e. g. Spectrum Database, Sensing, Beaconing etc.)
- Socialize the adoption of these techniques with various working groups OR start a new project on Spectrum Access System (Spectrum Database)
- Establish liaison relationships with organizations like the National Spectrum Consortium.

IEEE 802 Needs to Act Now to be Relevant to New Spectrum Bands

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Straw Poll for Questions at the End of this Tutorial

- Is the IEEE 802 Community interested in accessing Shared Spectrum?
- Is the IEEE 802 Community interested in Shared Spectrum Solutions for 5G?
- There are three initial steps to turn Spectrum Sharing Technologies into Standards – IEEE 802 Executive Committee Study Group, Working Group Study Group or Industry Connections Activity
  - Should we form an EC Study Group to understand the problem of Spectrum Sharing and follow-up Activities?
  - Should we form a WG Study Group to understand the problem of Spectrum Sharing and follow-up Activities?
  - Should we form an Industry Connections Activity for Spectrum Sharing and follow-up Activities?
- Should IEEE 802 engage in creation of a Protocol to Access the Spectrum Database (Spectrum Access System)? (e. g. IETF Protocol to Access White Spaces - PAWS)
- Should IEEE 802 engage in creation of a standards for Beaconing?
- Which of the 5G bands are of most interest to the IEEE 802 Community?