Networking and Information Technology Research and Development Program

Radio Receiver Systems:
R&D Innovation Needs and Impacts on Technology and Policy

May 05, 2017,

National Science Foundation

WSRD Workshop IX

Wireless Spectrum R&D Interagency Working Group

Welcome and Opening Remarks

Rangam Subramanian,

NTIA and WSRD IWG Co-Chair

Opening Panel

Moderator

Tom Taylor, OSD

Panelists

Jeff Boksiner, Army

Jeff Reed, Virginia Tech

Michael Fitz, Silvus Technologies

Chet Kanojia, Starry

Craig Scott, Ofcom

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Session I: Characteristics Needed in the Radio Receiver System

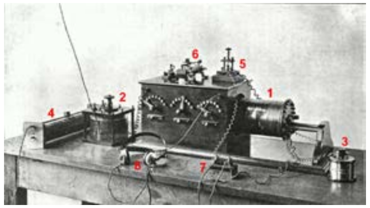
Radio Receiver Systems: R&D Innovation Needs, and Impacts on Technology and Policy (Wireless Spectrum Workshop IX)

Dr. Jeffrey Boksiner, ST
Senior Research Scientist (Electronic Warfare Technology)
Intelligence and Information Warfare Directorate (I2WD)

05 May 2017

Why Focus on Receivers

- **Radio receiver technologies are crucial to support operations in a contested, congested, and competitive Electromagnetic Operational Environment (EMOE)**
  - Determines ~ ½ system performance
  - Is the element of the system actually subjected to interference
  - Benefitting from significant technology advancements and R&D



Sensors

Electronic Support / Attack

Positioning, Navigation, and Timing

Networks

Receiver Needs
Contested/Congested EMOE Perspective

Flexibility/Adaptability
- Broadband
- Frequency agile / rapidly tunable
- Multi-function / multi-mission

Potentially conflicting technology needs

EMOE Situational Awareness
- Sense out-of-band
- Sense opportunistically and/or concurrently with desired reception
- Enabler for dynamic spectrum operations

Selectivity (analog/digital)
- Frequency
- Directional/Spatial
- Signal space
- Dynamic range

Constraints in cost & SWAP

Receiver Characterization

- **Proper characterization provides foundational data for analysis and planning tools**
- **Longstanding characterization techniques/measurement methods exist**
- **Research challenges**
  - Complex, adaptive, multi-mode systems
  - Efficiency and automation
  - Compatibility with current analysis/planning paradigms
  - Current tendency is to use the “envelope” of multiple properties
  - Theoretical models of receiver processing

METRIC

MIL-STD-449D
22 FEBRUARY 1973

SUPERSEDING
MIL-STD-449C
1 MARCH 1965

MILITARY STANDARD

RADIO FREQUENCY SPECTRUM
CHARACTERISTICS
MEA SUREMENT OF

FSC EMCS

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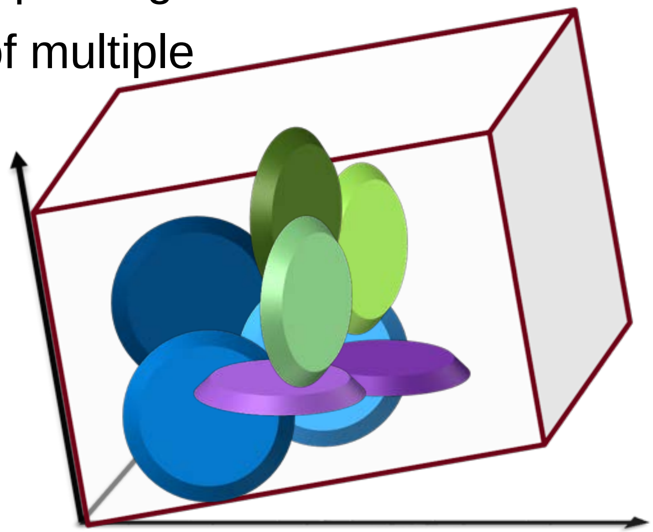

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WSRD Workshop IX

Radio Receiver Systems: R&D Innovation Needs and Impacts on Technology and Policy

Challenges and Research Opportunities in Receivers: Design, Characterization, and Management

Jeffrey H. Reed and Aditya V. Padaki

Email: reedjh@vt.edu

Wireless @ Virginia Tech

BRADLEY DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Research Sponsored By:

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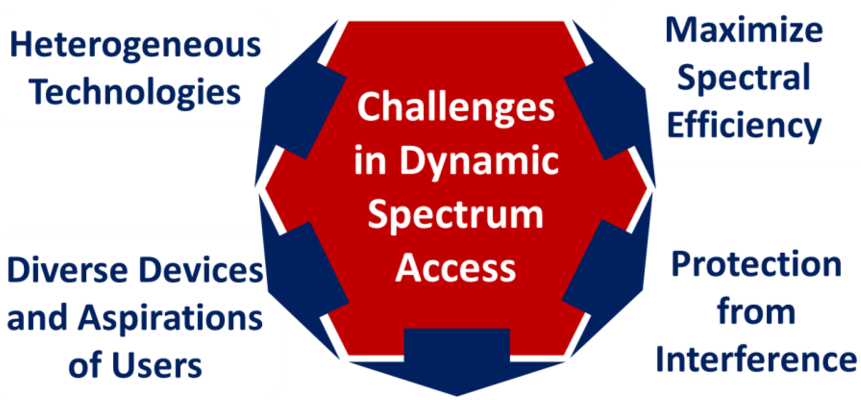
WHERE DISCOVERIES BEGIN

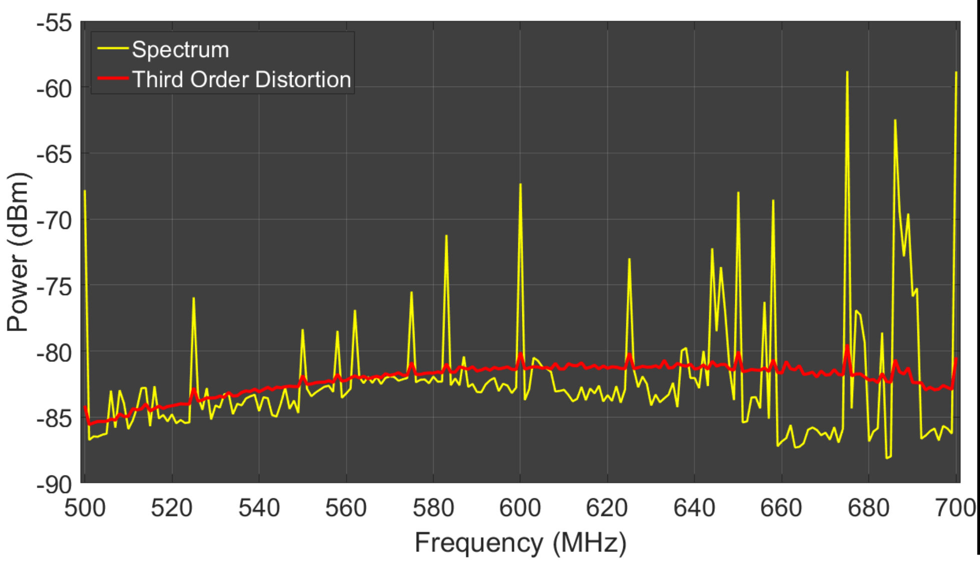
Disclaimer: Any opinions and/or findings are that of presenters' own and does not necessarily represent the views of the National Science Foundation

An Overview



How to manage the spectrum dynamically, extract every Hz and provide protection from harmful interference?
Solution: Use Receiver Characteristics

Spectrum of Washington D.C between 500MHz and 700 MHz



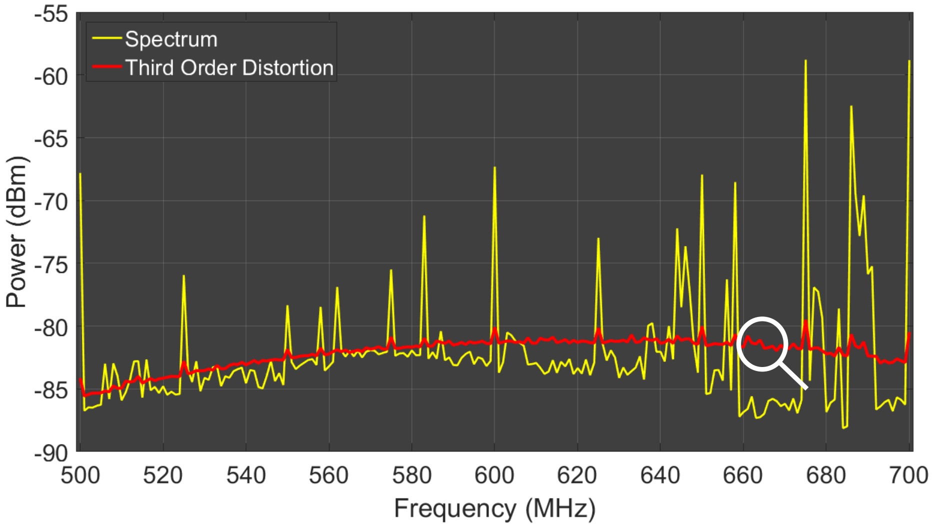
Research on Better Receiver Design

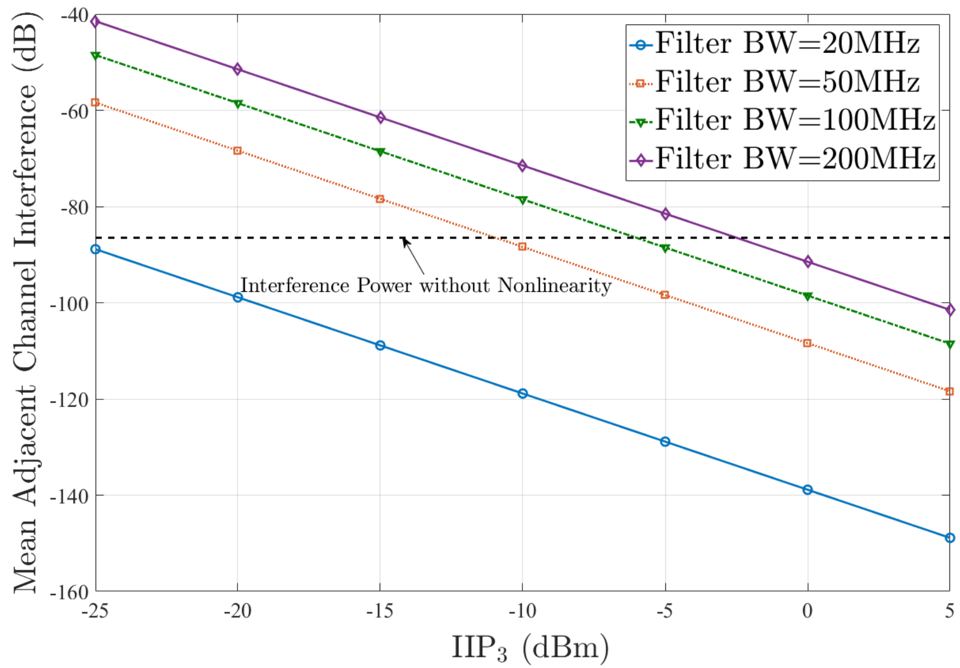
- Better RF/mmWave Filters: Can MEMS help?
- Change Dynamic Range dynamically: Software Defined
- Detection & Mitigation of "Intermodulation Jamming"
- Heat sensitivity and stability of phase noise and noise floor, especially in mmWave systems
- How to use smart antennas – for both mmWave & Microwave systems to help spectrum sharing
- Cognitive Waveform Design

Research for Regulatory and Standardization Efforts

- Developing standardized metrics to quantify "harmful interference" – use nuanced soft decisions
- Extensive measurement campaigns for co-existence analysis and quantifying performance detriment
- Standardized quantifiable metrics for receiver performance; simplified metrics to convey consumer
- Use these metrics for spectral assignment with SAS
- Regulatory frameworks for spectrum sharing with next generation SAS: More dynamism and robustness (Currently spectrum request has to be 24 hours prior)

Example of receiver vulnerabilities – Increased noise floor Interplay between non-linearity and pre-selector bandwidth





- Variation of Mean Interference Power
- Measurements between 660-670 MHz
- Different IIP3 and front end filter Bandwidths for the measured spectrum

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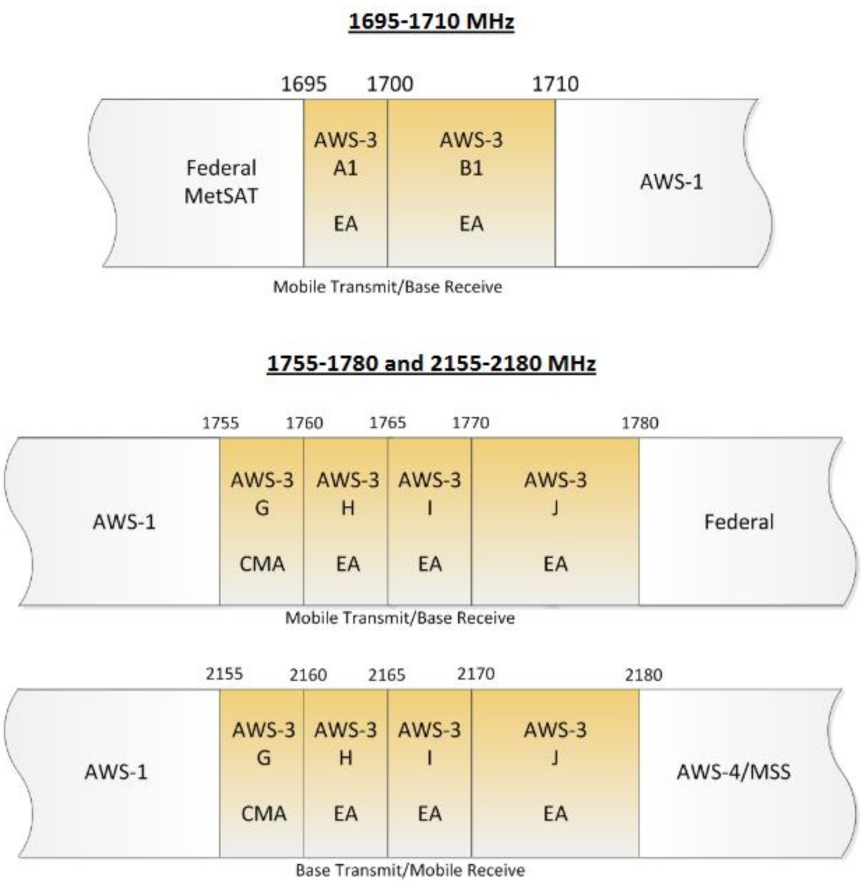
Similar Issues May arise in AWS-3 Band

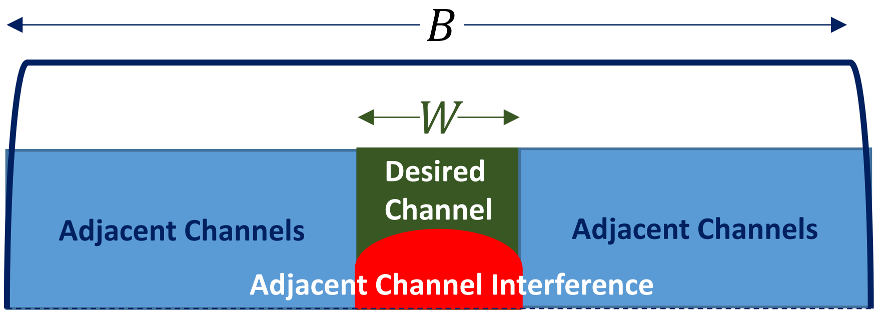
- The band plan is as shown
- This will be shared with military systems
- AWS and military may operate in adjacent channels
- Potential adjacent channel interference issues



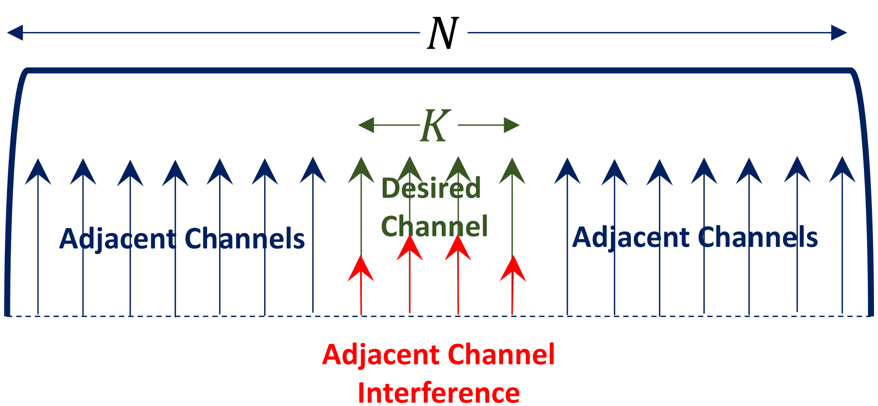
Wireless @ Virginia Tech

How much detriment does nonlinearity cause?
Analysis with Ratio of ‘Signal to Pre-selector Bandwidth’

Reference Input Spectrum for Quantifying



$\beta = \frac{W}{B}$ = Ratio of Signal Bandwidth to Pre-Selector Bandwidth

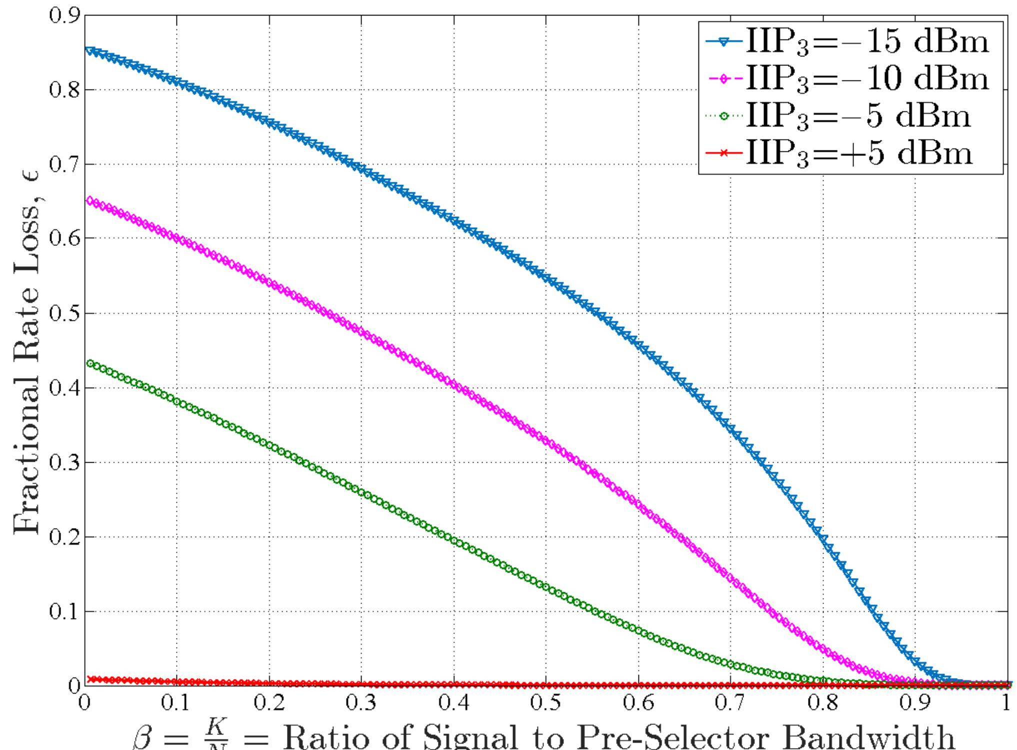


Discrete domain input:

Multi-tone sinusoidal input, $\beta = \frac{K}{N}$

Fractional Rate Loss

Pre-selector BW, $B = 150$ MHz, $P = -60$ dBm



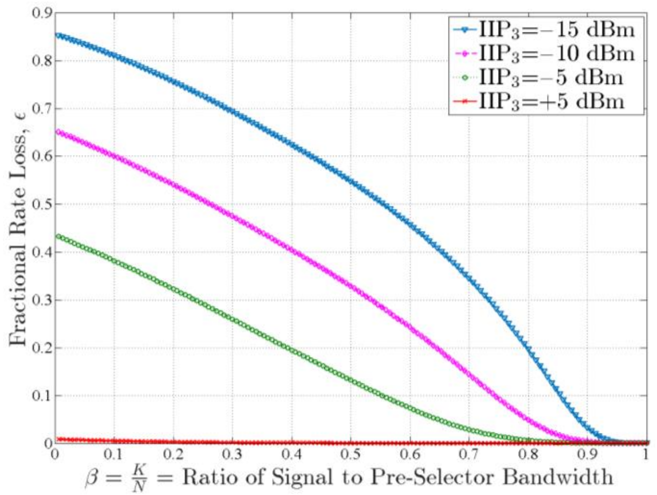
Sample IIP3 values for RF chains:

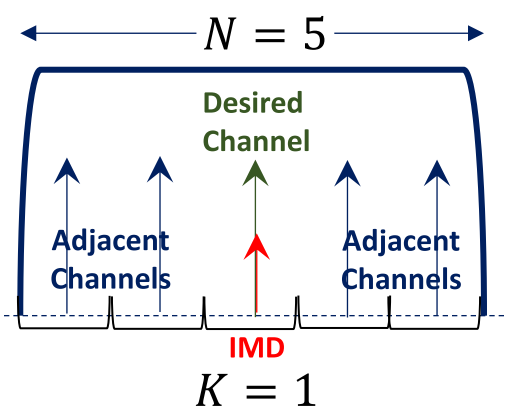
WiFi Routers: –20 dBm to –10 dBm

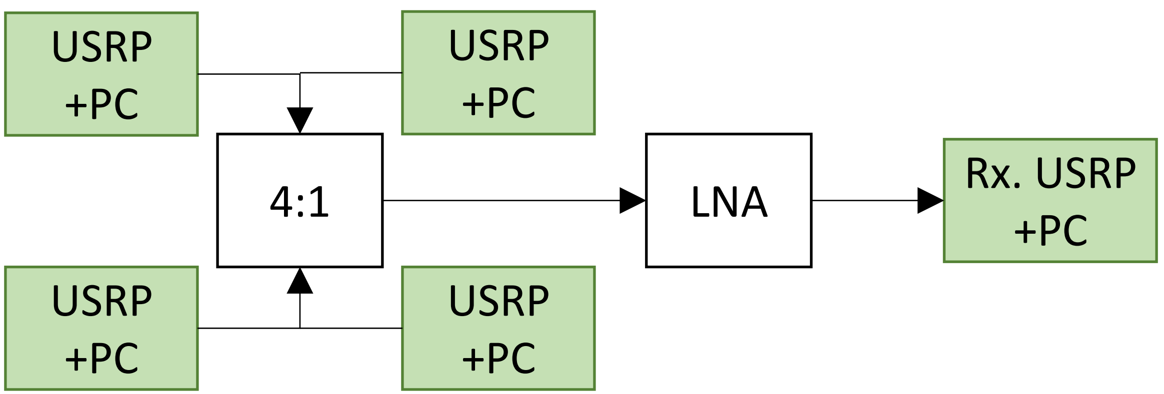
LTE: –5 dBm to +5 dBm

Proposed Laboratory Measurement of Fractional Rate Loss

- Analysis of fractional capacity loss gave that plot
- How to re-create that in the lab?
- Use USRPs: 5 channels, each 1.5 MHz wide
- Measure the IMD for the reference multi-tone input
- Power of each tone=total power in the channel
- **Extensive development of experimental and validation techniques required**



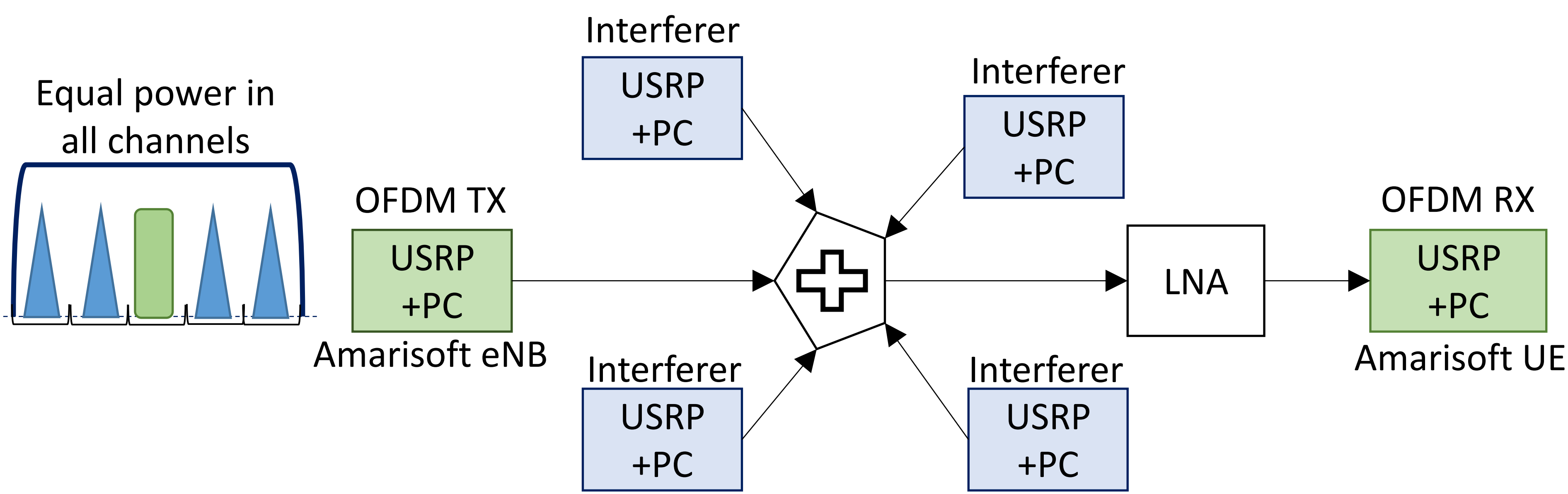




Wireless @ Virginia Tech

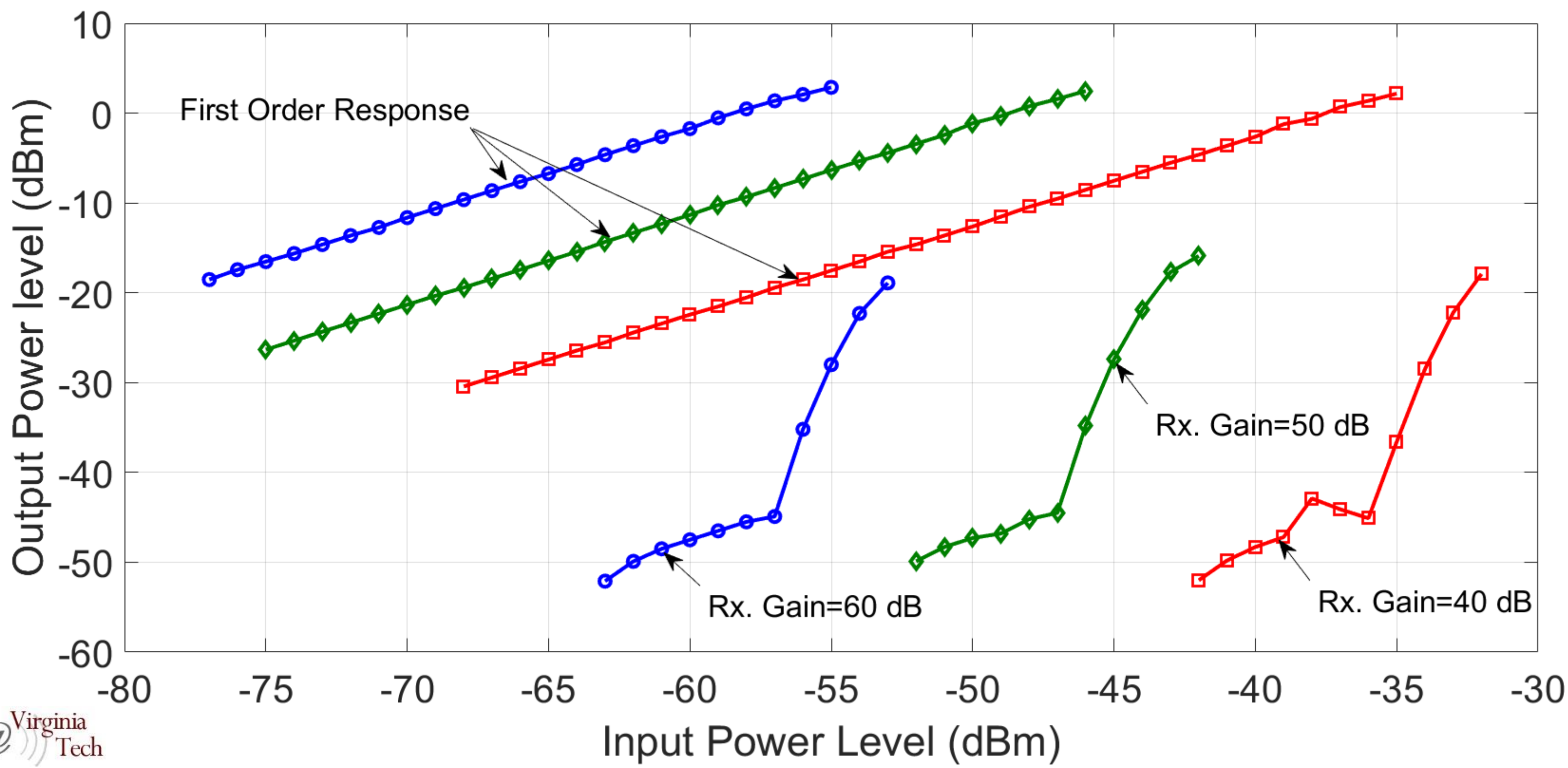
Proposed Measurement of Performance Detriment for LTE

- Desired Tx-Rx OFDM with Amarisoft
- Measure Throughput with and without interferers
- <u>Clear calibration and nonlinearity (IIP3) measurements necessary</u>
- Compare with Theory (analysis with multi-tone inputs)
- **More such standardized techniques need to be developed**



Our measurements in understanding USRP: Two-tone Test

- IIP3 measurement and calibration of USRP B210: For different analog RF gains
- Third order measurements had a slope of 6 on transfer characteristics!
- Currently investigating the reason:
  - May be because of ADC nonlinearity overriding front end nonlinearity
- **Makes a case for clear understanding and evolving standard test procedures**

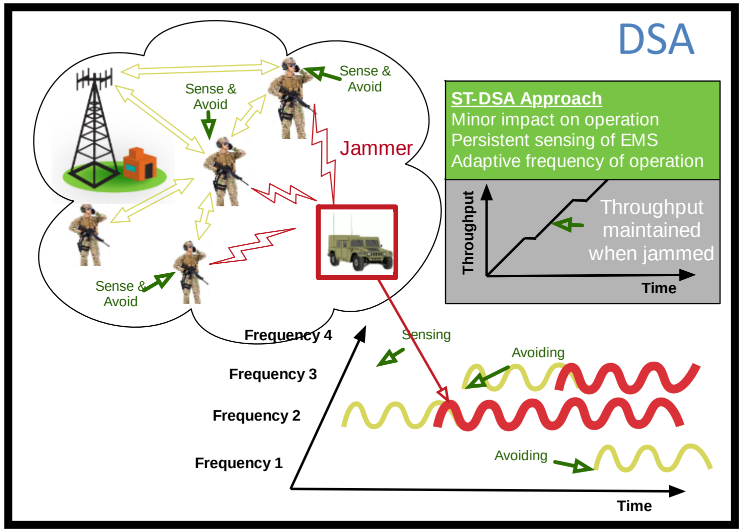


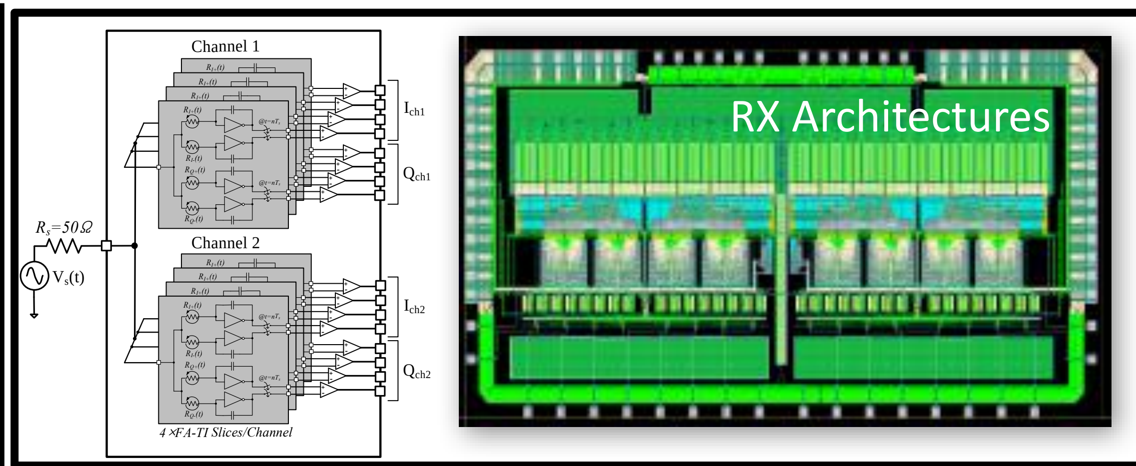
Conclusion

- Efforts to quantify and understand receiver performance needed
- Standardized test and evaluation procedures need to be developed for receivers
- Lot of research opportunities from a receiver perspective to make spectrum sharing effective exists

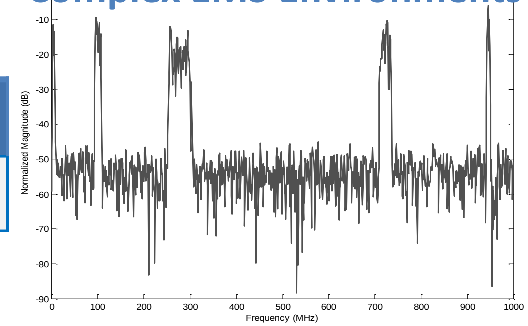
Thank you!

RX Technology for the Era of Congested/Contested Spectrum Access





Complex EMS Environments

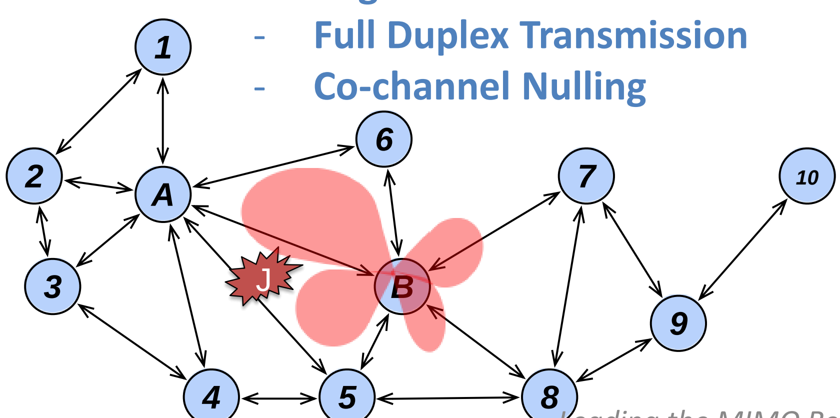


Stringent Performance Requirements

Noise Figure	Linearity, IIP3	Resolution	Scan Time	Bandwidth	Power draw	Size/Weight
<3dB	20dBm	50 KHz	600us	0.001 - 6 GHz	500 mW	3 cubic inch 200 grams

Nulling Interference

- Full Duplex Transmission
- Co-channel Nulling

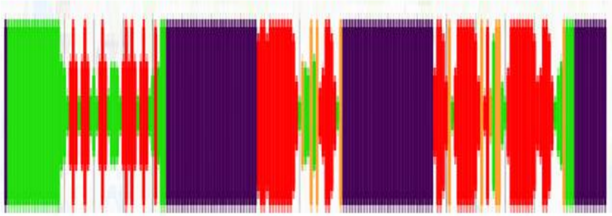


Regulation of Receivers, Improving RF Performance and Spectrum Sharing

Craig Scott, Senior Technology Analyst, Spectrum Group, Ofcom

5 May 2017

Regulation of Receivers, Improving RF Performance and Spectrum Sharing



Increasing spectrum demand and the need to share

Challenges with receiver performance and co-existence

The UK need to regulate receivers

The regulatory framework adopted

Importance of standardisation

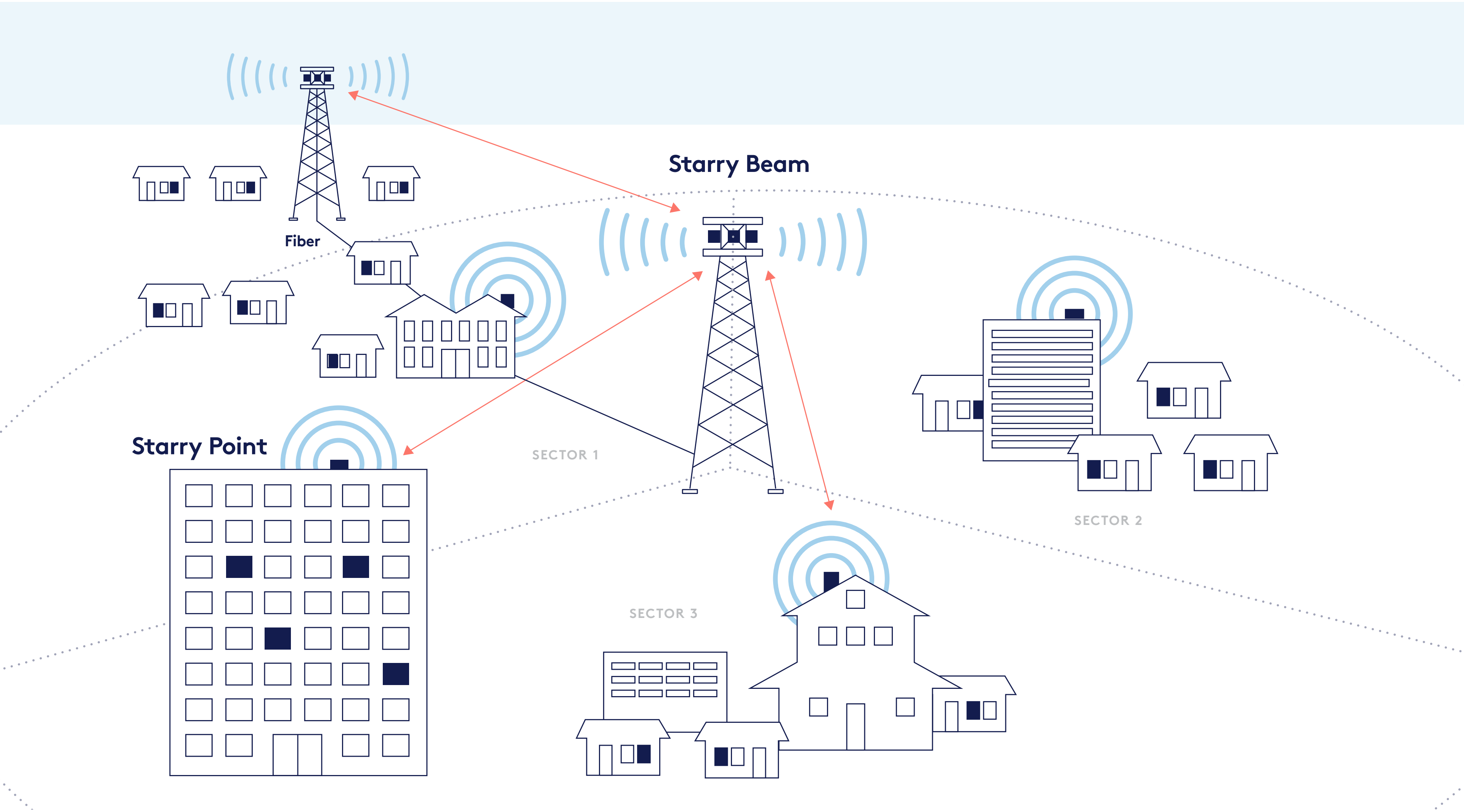

ETSI EN 303 340 V1.1.2

HARMONISED EUROPEAN STANDARD

Digital Terrestrial TV Broadcast Receivers;
Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU

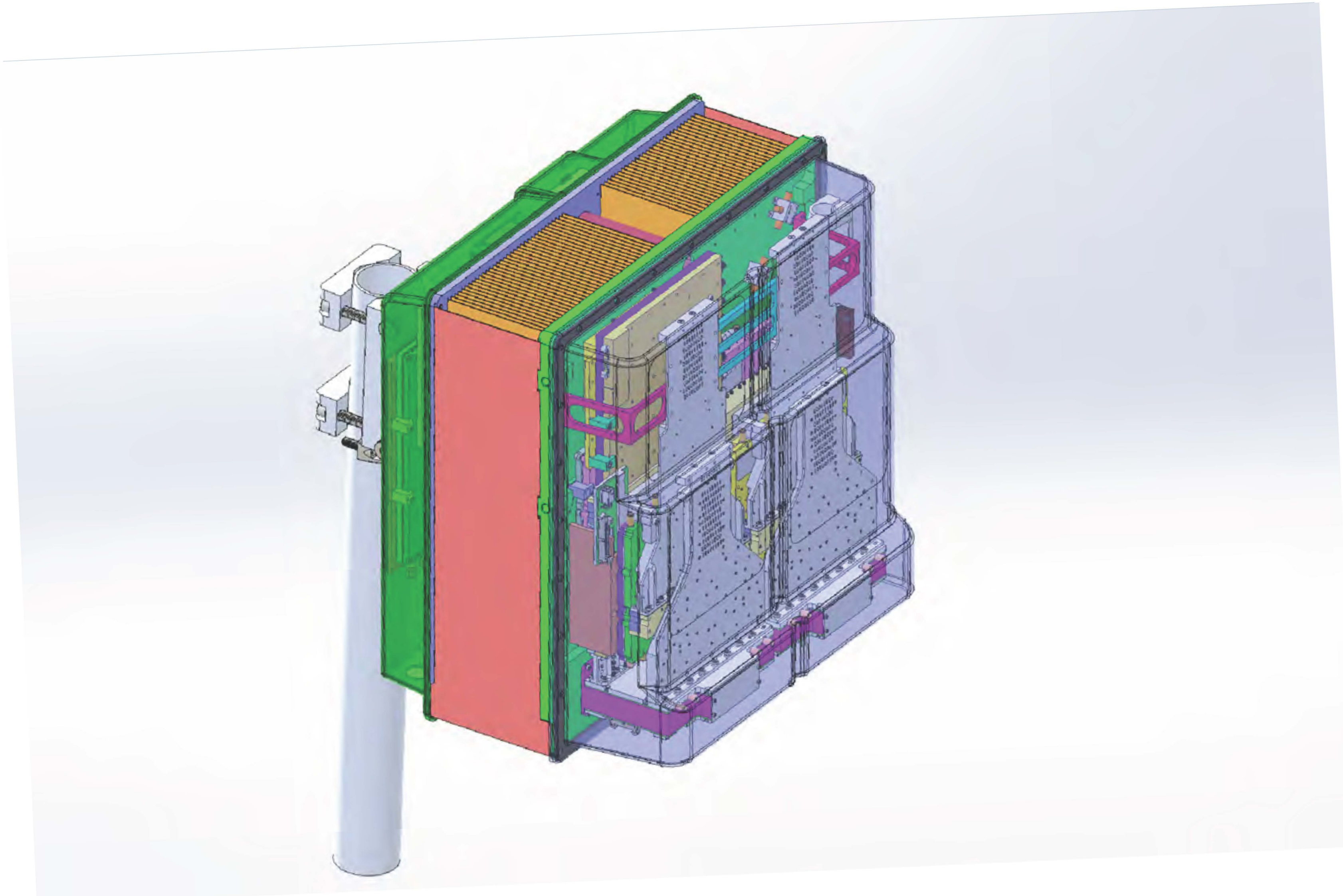
Introducing Starry’s Tech Stack

Starry Internet



Starry Beam: Integrated Base Station

Starry Beam: Inside the Radome



Starry Beam: Integrated Base Station

KEY FEATURE OR INNOVATION	CONSUMER BENEFIT
MU-MIMO AT MM WAVE ON 160 MHz WIDE CHANNELS	5 Gbps per sector in a compact integrated package, and up to 20 Gbps per site in this generation, going to up to 50 Gbps in next generation. Enables cost effective high speed consumer offering
ACTIVE PHASED ARRAYS	RANGE up to 2km
COMPACT AESTHETIC DESIGN	Integrated Package including Antennas

Starry Points: Flexible End Point Configurations

TYPE	APPLICATION
Starry “Spire”	Architecturally Controlled Condominiums, Brownstones, Triple-Deckers
Starry “Castle”	Single Family Homes, with single hung or double hung windows
Starry Point	Multiple Dwelling Units of of >= 10 units

Starry Point: MDU Configuration


Starry Point: Concealed Install

Starry Point: Single Family Unit Configuration

Starry's Proposal for mmWave Spectrum Sharing

Sharing Technique

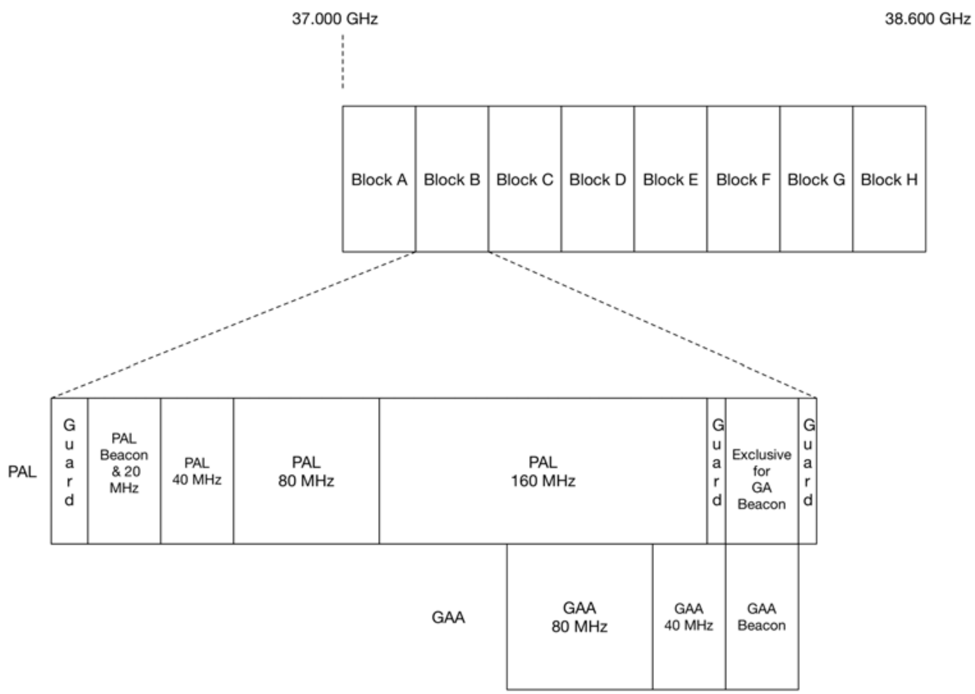
Scope

- Proposed for 37.0 ~37.6 GHz, suitable for others
- Suitability: High Bandwidth, Low Latency Fixed, Mobile and Earth Station
- Duplexing: TDD, FDD
- PALs & GAA

Sharing using a Radio-Based Strategy

- Extend with real time prioritized slotted reservation system inspired by 802.11 with control by APs
- Guarantee some bandwidth to PALs, provide priority to PALs for shared, and permit GAAs to use most, as available
- PALs could aggregate channels to e.g. 600 MHz / 800 MHz and leaves room for FDD, TDD & 2xTDD
- Geographic protection for government users
- Provides guaranteed PAL bandwidth for low latency
- Encourages new entrants and competition
- GAAs able to use about half of spectrum
- Potential for SAS-based system for ultimate conflict resolution, not for providing coordination

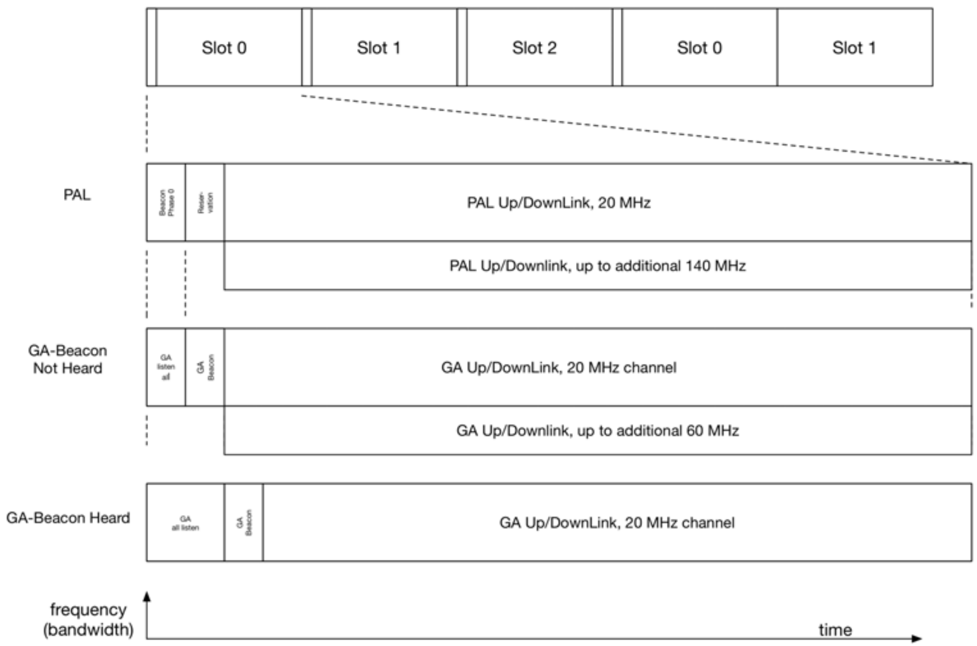
Sample Band Plan 37.0 ~ 38.6 GHz



Principles

- Divide into 200 MHz Blocks
- PAL for each block or sets of blocks
- PAL's APs offer timed beacons based on 802.11, readily decodable
- PALs use up to 160 MHz of the 200 MHz Block
- GAAs allocated 20 MHz but can use up to 80 MHz
- GAAs could be other PALs acting as GAAs in Block

Media Access Control (MAC) Proposal



<u>Principles</u>

- Slotted reservation system (3 shown), based on uplink and downlink traffic requests + QoS
- PAL AP Beacon at regular interval
- All STAs and GAA listen for Beacon
- PAL STAs quiet during beacon period and can use CS/CSMA or RTS/DTS slots / Bandwidth under control of AP
- Up to 160 MHz available for PAL
- Unused PAL slots provide up to 80 MHz for GAA
- GAA usage could be full block if PAL not operational in geographic location

Tutorials: *State of the Art*

Frank Sanders, NTIA-ITS

Jeremy Muldavin, OSD

Pierre de Vries, FCC TAC

WSRD IX

Receiver Design & Documentation Best Practices: A 10-Minute Tutorial

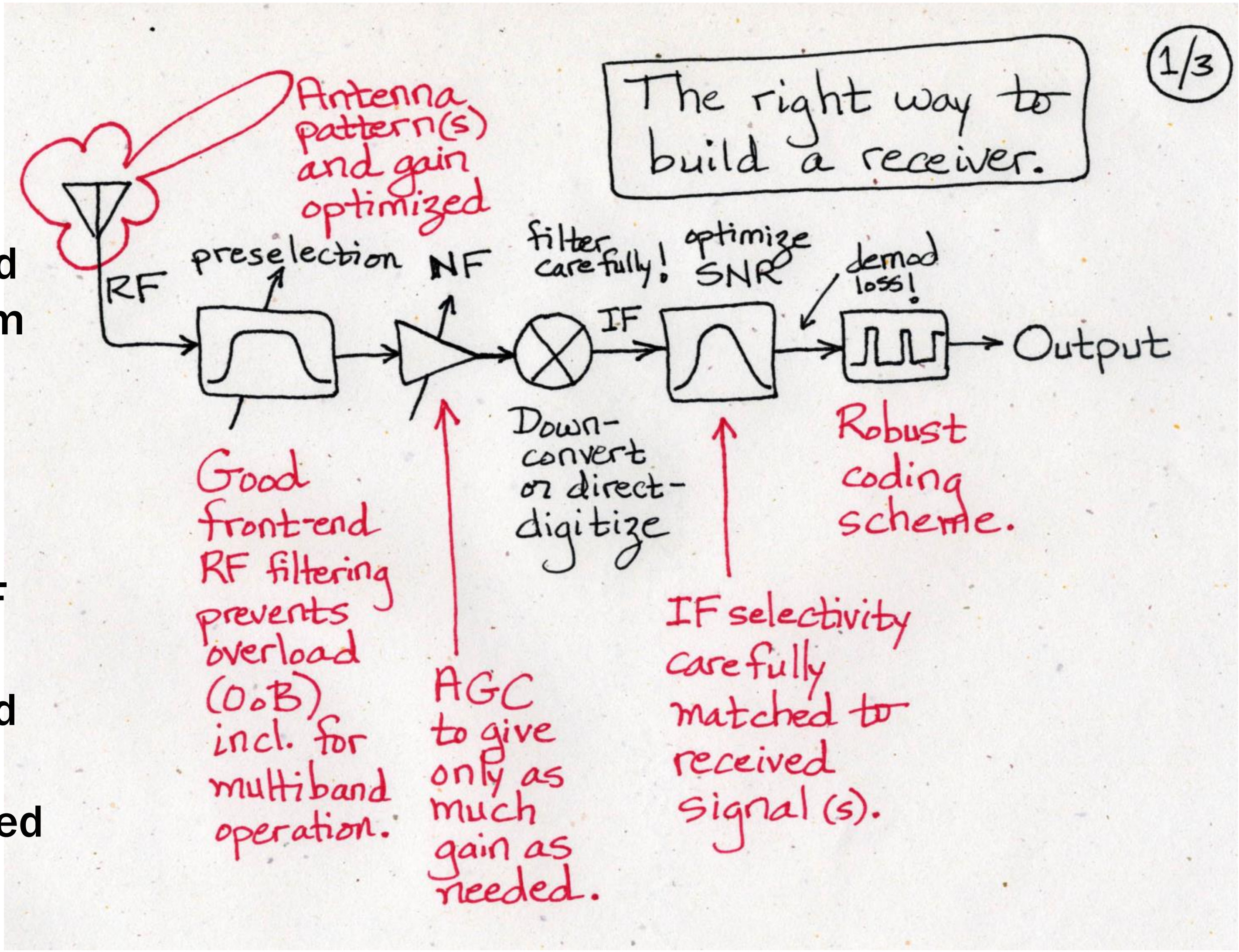
5 May 2017

Frank Sanders, Senior Technical Fellow
NTIA/ITS – Boulder, Colorado
Fsanders@ntia.doc.gov

Properly Designed Receivers

Well designed receivers are carefully optimized at every stage from antenna to final output.

Antenna characteristics, RF filtering, gain characteristics and IF characteristics are all well-matched to mission needs.



Measured, Not Just Spec'ed

Every characteristic of a receiver design needs to be assessed via measurements, and not simply spec'ed.

Actual characteristics are nearly always better than specs.

Publish or archive the receiver performance data for later retrieval.

2/3

Receiver Technical Characteristic	Specified	Measured
Antenna patterns	✓	✓
Antenna frequency response	✓	✓
RF front end filter loss	✓	✓
RF front end filter shape(s)	✓	✓
RF front end passband BW(s)	✓	✓
Front end LNA gain (AGC)	✓	✓
Front end LNA noise figure	✓	✓
Front end LNA 1-dB compression	✓	✓
Downconversion characteristics	✓	✓
IF filter shape(s)	✓	✓
Demod losses	✓	✓
Coding scheme(s) & spectra	✓	✓

Determine and record actual system characteristics of receivers, not just specs.

Specs are usually in system requirements docs.

Either publish or archive so that anyone can find and retrieve 50 years later.

Receiver Lessons Learned

3/3

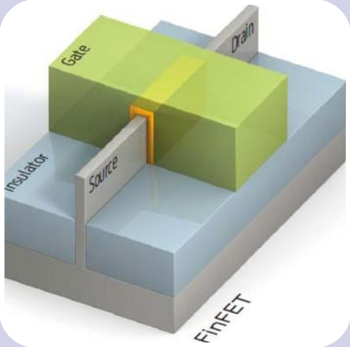
Spectrum sharing lessons learned for receivers:

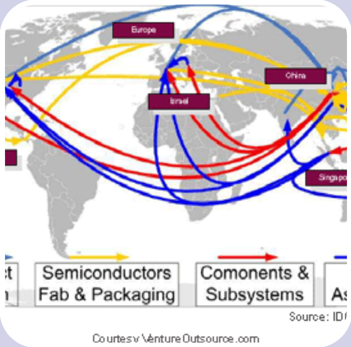
- Poor receiver design (e.g., lack of front-end filtering or too much gain in frontend LNA(s)) can cause or contribute to interference problems. (Comes up in sharing scenarios.)
- Actual, not just specified, receiver characteristics need to be known and either published (ideal) or else archived in a locatable, retrievable manner.
- Receiver designs may last 50 years or more.
- Receiver characteristics need to be known for effectiveness in interference investigations.
  - Helps to determine whether "interference" is a receiver artifact, e.g. front-end overload.
- Field staff who are troubleshooting interference reports need to know (be able to look up) and understand receiver characteristics in context of how interference artifacts may manifest in receivers.

DoD Needs for State-of-Art Radio Systems
May 5, 2017

Dr. Jeremy Muldavin
Office of Deputy Assistant Secretary of Defense, Systems Engineering (DASD(SE))

Microelectronics Trends





State-of-the-art Devices

- Deeply-Scaled Silicon ICs (14nm)
- 2.5 & 3D ICs
- Heterogeneous System-on-Chip (SoC) ICs
- Flexible and miniature packaging
- Accelerator and SoC architectures

Increasing Cost and Complexity

- $5-15B for a modern fabrication facility
- >$500M for a new commercial smart phone SoC development
- Reliance on third-party Intellectual Property (IP)

Globalization and Commercial Dominance

- State-of-the-art fabrication consolidation
- Commercially-driven (DoD <1% of market)
- Complex global supply chain
- China investing heavily ($150B)

New Applications

- Internet of Things
- Big Data systems
- Autonomous systems
- Spectral and spatial communication agility

Commercial Computing Trends

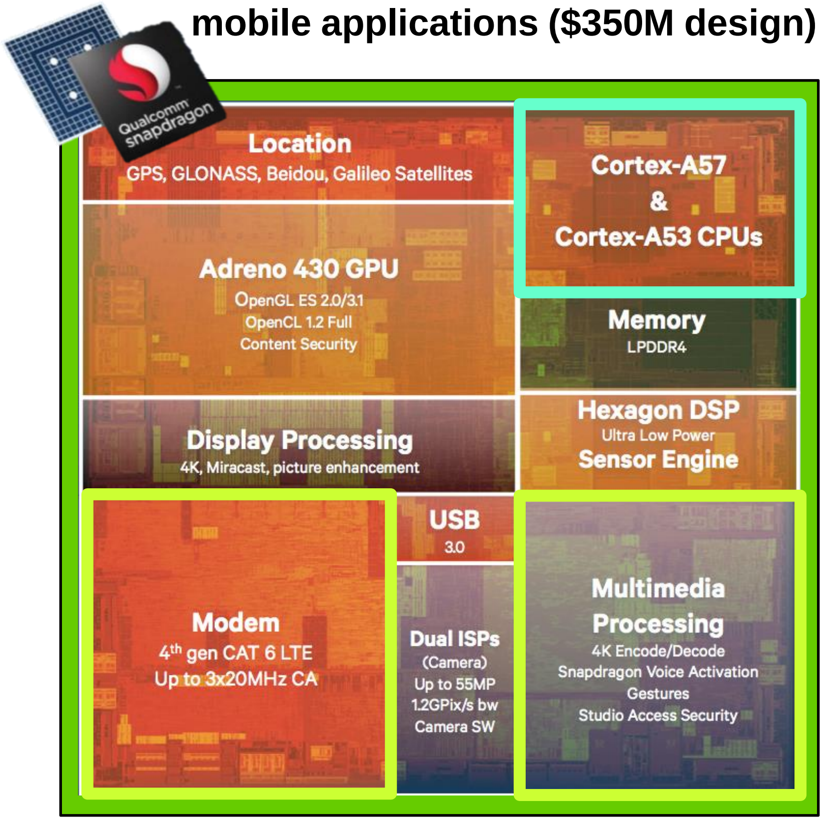
Mobile Computing

Internet of Things & SDR

Powerful Test & Measurement

Cloud Computing & Infrastructure

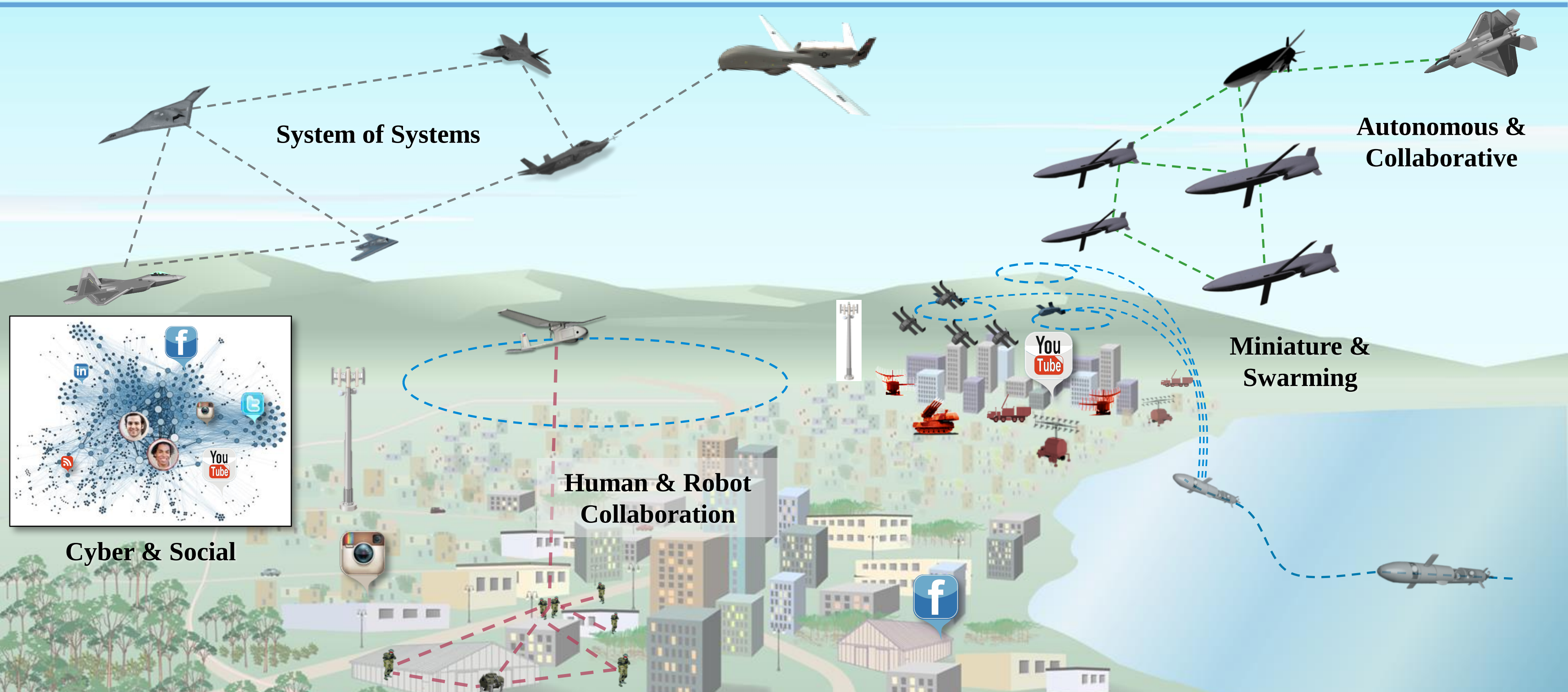
Commercial System on Chip (SoC) for mobile applications ($350M design)



Global mobile computing & infrastructure brings powerful capabilities to EVERYONE

Accelerators enable 10-1000x capabilities in SoC and server architectures

Future Warfighting Systems
Advanced Microelectronics Needs



Big Data & AI Systems

Artificial Intelligence (AI) and Graph Processors

- 100B-1T node graphs
- Need 1000x performance and efficiency for real-time

Decentralized Systems

Open & Distributed Architecture & Processing

- Local processing raw data
- Rapid tech. insertion & upgrades using SotA

Human & Robot Systems

Vision, Semantic & Navigation Processing

- High performance imagers & local processing circuits
- Robust Navigation & local semantic processing

Diverse Protected Links

Frequency & Antenna Diversity Signal Proc.

- Multi-antenna & frequencies
- Adaptive processing (Trillion Ops/sec/Watt) for robust comm. & radar systems

Global Tech & Infrastructure

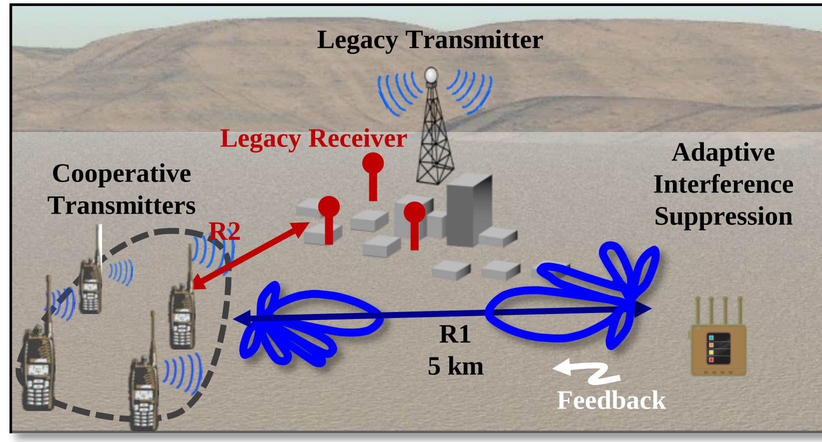
Leverage & Assure Access to the best Technology

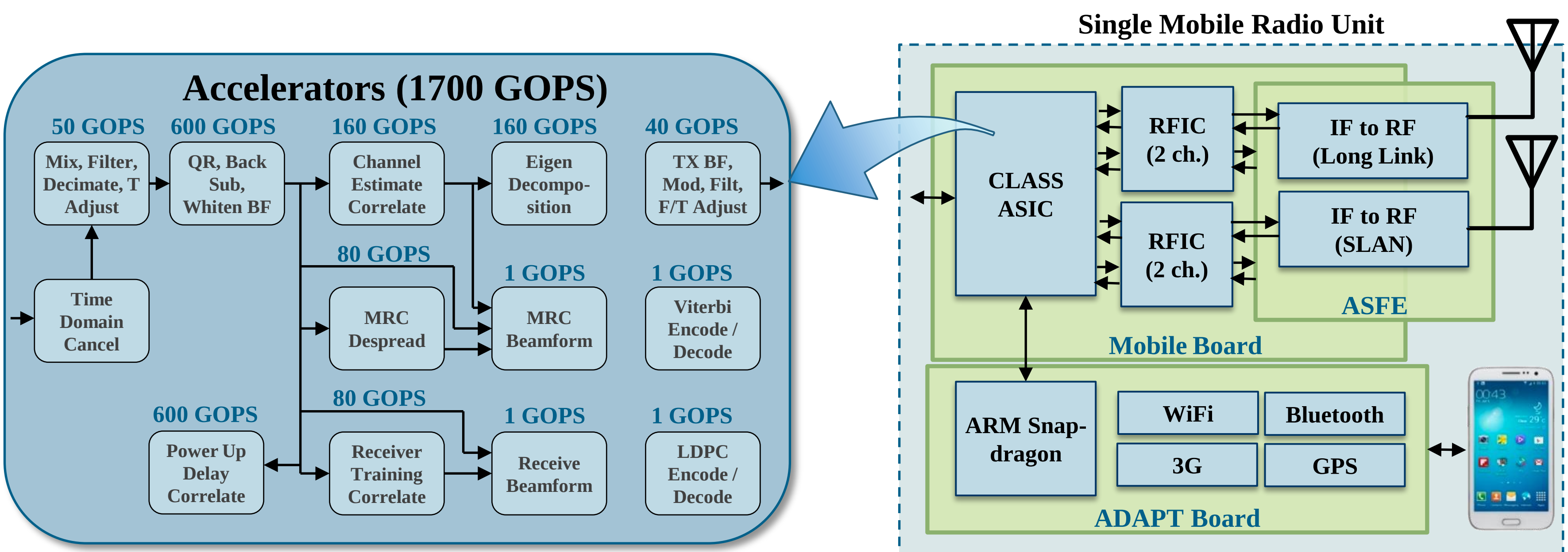
- Use best global tech where it exists
- Assure Domestic sources for state-of-art

A DoD SoC Example

Leverages extreme ASIC computational technologies

- **Coherent beam forming, adaptive nulling and interference cancellation:**
  - **5-10X range extension or 1000x lower power**
  - **10000 interferer to signal ratios**
- **Mobile radio form factor achieved by ASIC accelerators with 1.7 TOPS/W**





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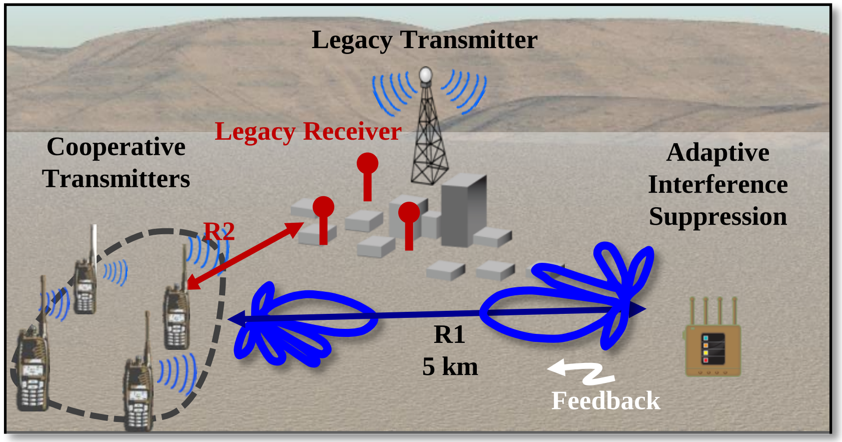

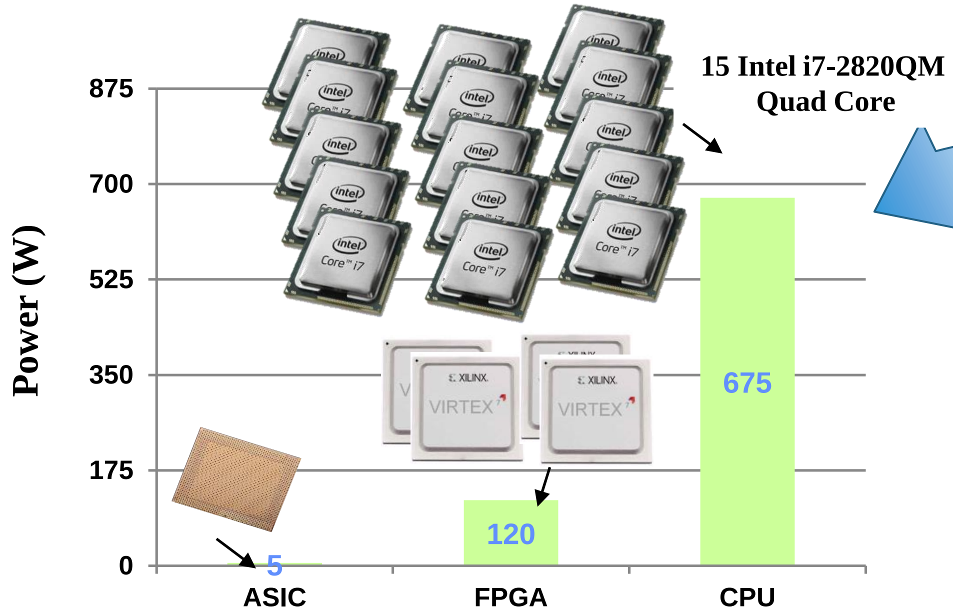

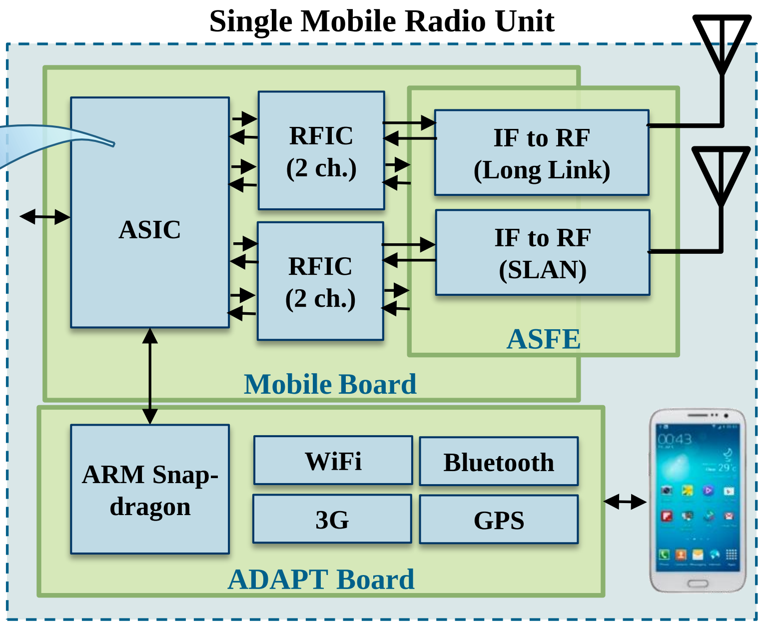

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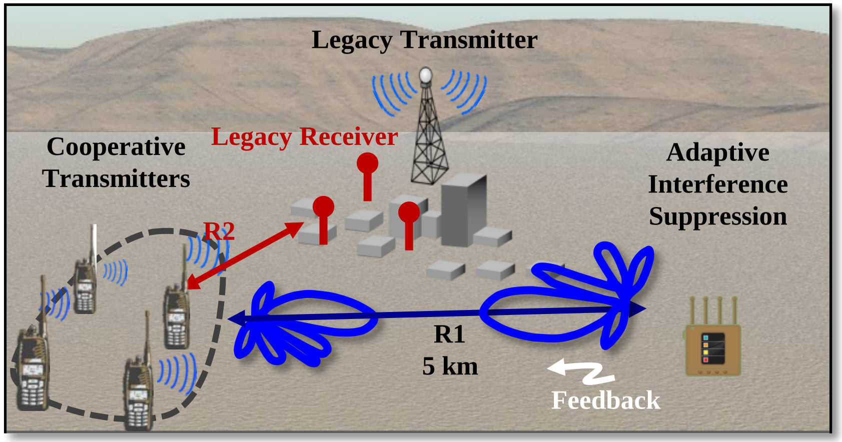
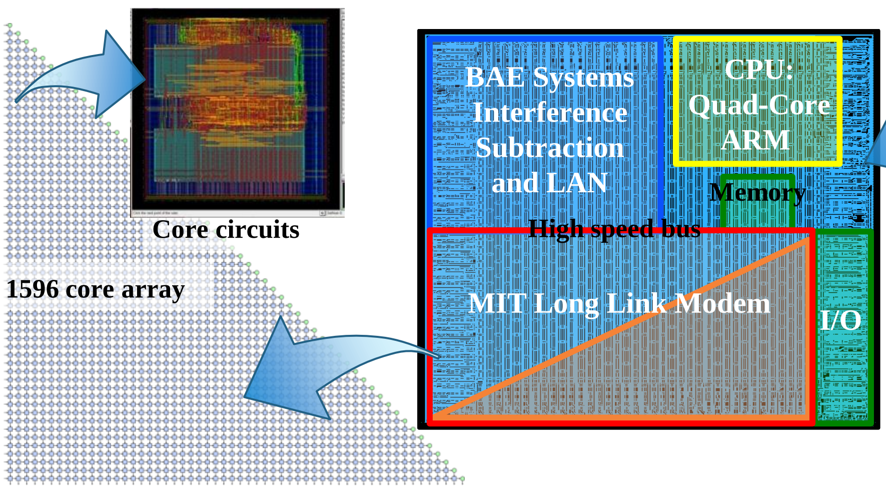
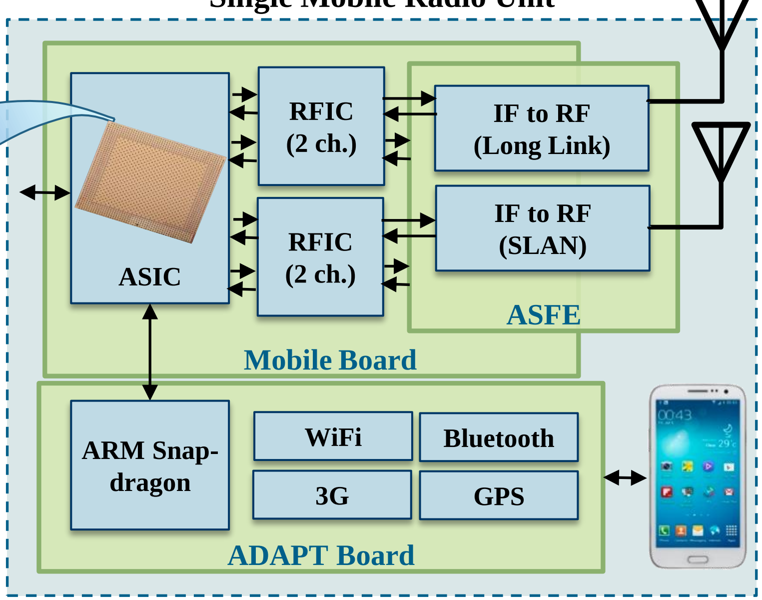




1.7 TOPS/W System on Chip for MIMO Communications Applications

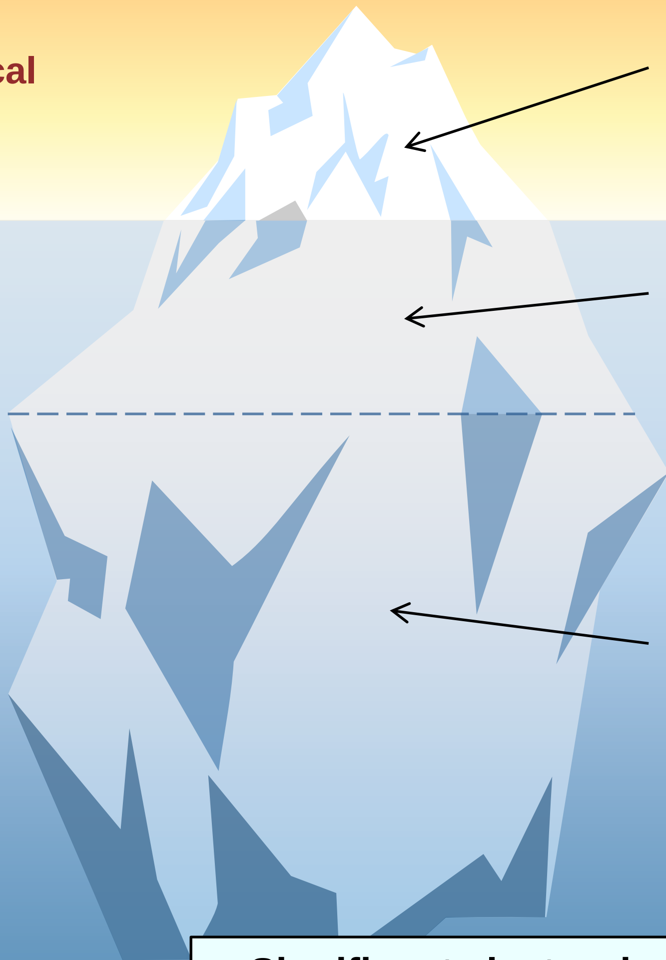
Single Mobile Radio Unit



Electronics as a Strategic Issue

Current Tactical Issue

Larger Strategic Issue



DoD Trusted Electronics Issue

- Options for domestic trusted manufacture of custom DoD electronics are diminishing

COTs Electronics Trust (DoD & Beyond†)

- Most COTs electronics used in DoD systems are fabricated overseas; significant risk from tamper
- Risks similar for the broader national security community, banking, critical infrastructure, etc.

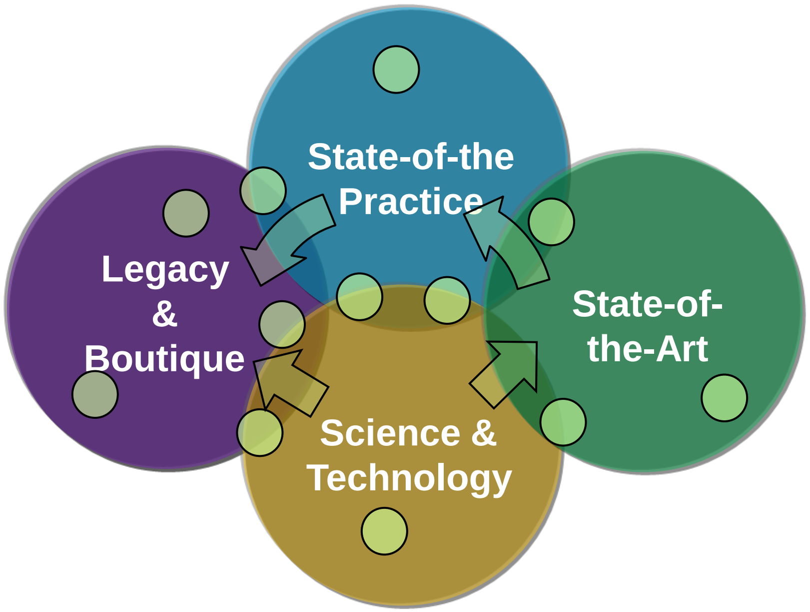
Access to Electronics / Electronics based economic growth

- Shift in electronics fabrication creates potential for overseas control
- End of Moore's Law potential carries economic impacts

Significant electronics challenges represent a strategic level national issue

† Including the broader national security community, banking, critical infrastructure, commercial industry, etc.

Microelectronics Assurance Domains & Concerns



Availability

- Assured and expanded supply chain for specialized microelectronics for DoD systems
- Increased assurance and expanded supply options for Legacy parts

Access

- Lower barriers to safely access and develop advanced semiconductor-based systems to address new threats
- Robust design & validation tool access

Assurance

- Leverage an assured global supply and partners in U.S. semiconductor industry
- Competitive advantage for new markets through enhanced assurance practices

ASIC

- Dense Digital CMOS
- RF & Mixed Signal
- Compound Semiconductors

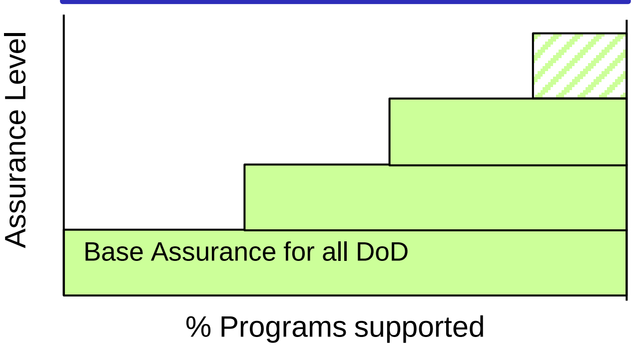
FPGA

- Commercial SoC w/FGPA
- Rad-hardened
- Low-power

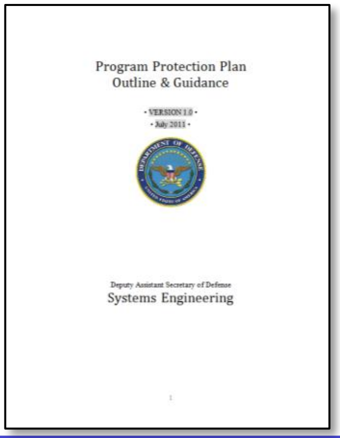
COTS

- Microcontrollers
- Analog components
- PcB assemblies

Assurance Tools

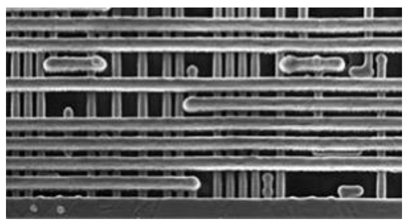


What We are Doing



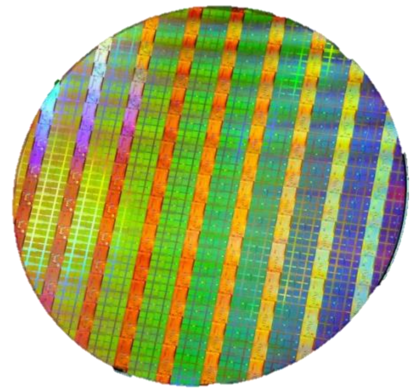
Policy

- DoD Instruction (DoDI) 5000.02
- Program Protection Plan (PPP)
- International Traffic in Arms Regulations (ITAR) update (in work)



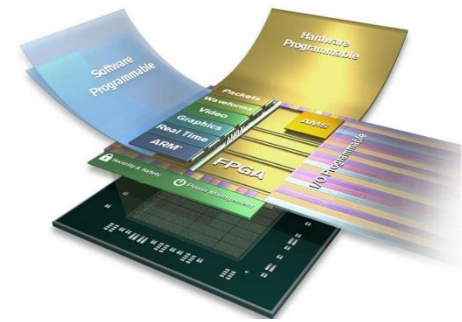
Joint Federated Assurance Center

- Software assurance knowledge & tools
- Hardware assurance knowledge & tools
- Advanced verification & validation capabilities



Trusted & Assured Microelectronics

- Access to state-of-the-art foundries
- Trust and assurance methods and demonstration
- Industrial best practices for assurance



COTS and FPGA

- Supply chain risk management
- FPGA Assurance Study
- Radiation hardened microelectronics initiative

Conclusions

- **Commercial System on Chip technologies are making radios and complex signal processing ubiquitous and mobile**
- **Department of Defense has real needs to access this technology for next generation communication systems**
- **The barriers to access this technology with assurance are significant**
- **DoD is pursuing policy, awareness, assurance, and national level microelectronics innovation to address this issue**

BACKUP

Harm claim thresholds

An alternative to receiver standards

WSRD Workshop IX: Radio Receiver Systems
5 May 2017, Arlington, VA

Pierre de Vries
Co-Director, Spectrum Policy Initiative

Silicon Flatirons Center for Law, Technology & Entrepreneurship
University of Colorado at Boulder

Summary

Harm claim thresholds:

A way to include reception in rights definitions
without mandating receiver performance

In-band & out-of-band field strength profiles
not to be exceeded at more than some % of locations
at some statistical confidence level
before a system can claim harmful interference

Simple to include in rules and measure in the field

TAC (2015) Principles for Assessing New Allocations

Interference Realities

1. Harmful interference is affected by the characteristics of both a transmitting service and a nearby receiving service in frequency, space or time
2. All services should plan for non-harmful interference from signals that are nearby in frequency, space or time, both now and for any changes that occur in the future
3. Even under ideal conditions, the electromagnetic environment is unpredictable. Operators should expect and plan for occasional service degradation or interruption. The Commission shall not base its rules on exceptional events

Service Responsibilities

4. Receivers are responsible for mitigating interference outside their assigned channels
5. Systems are expected to use techniques at all layers of the "stack" to mitigate degradation from interference
6. Transmitters are responsible for minimizing the amount of their transmitted energy that appears outside their assigned frequencies and licensed areas
7. Services under FCC jurisdiction are expected to disclose the relevant standards, guidelines and operating characteristics of their systems to the Commission if they expect protection from harmful interference
8. A quantitative analysis of interactions between services shall be required before the Commission can make decisions regarding levels of protection

9. The Commission may apply interference limits to quantify rights of protection from harmful interference

Receivers can be responsible for harmful interference

Service degradation can be due to receiving system design, not transmitted signals

- Insufficient selectivity
- Non-linearity
- Weak desired signal
- etc.

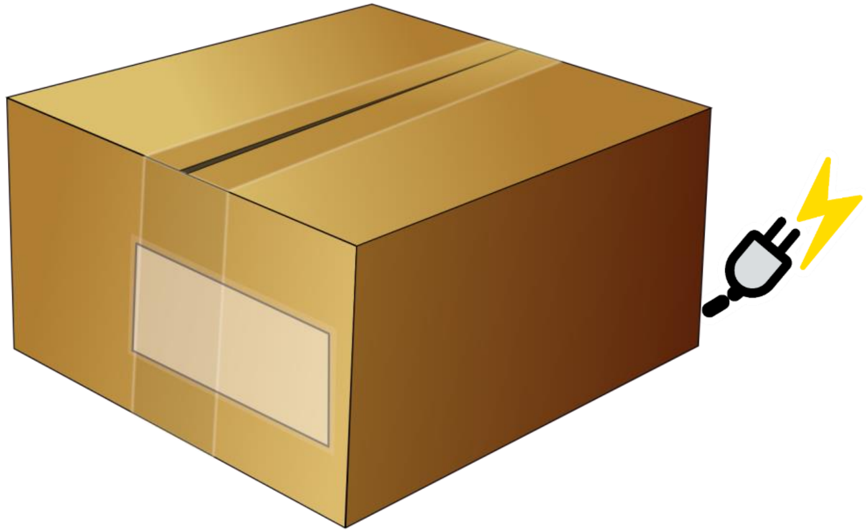
Examples “where receiver performance was a significant issue affecting access to the spectrum for new services” (FCC TAC 2011)

- GPS ← terrestrial cellular
- SDARS ← WCS cellular
- AWS-1 cellular downlink ← AWS-3 M2Z
- BAS ← AWS-1 downlink
- etc.

So: Receiver Standards?
(i.e. government-mandated receiver specs)

Repeatedly suggested, but seldom used:

- Receivers are very different from transmitters (cf. Cardboard Box Test)
- Receiver performance just one factor in a system's response to RF environment
- Hide or ignore trade-offs between Rx vs. Tx interests
- Manufacturers jealous of autonomy
- FCC's questionable statutory authority



BUT see: EU Radio Equipment Directive

Harm Claim Thresholds (HCTs) in Brief

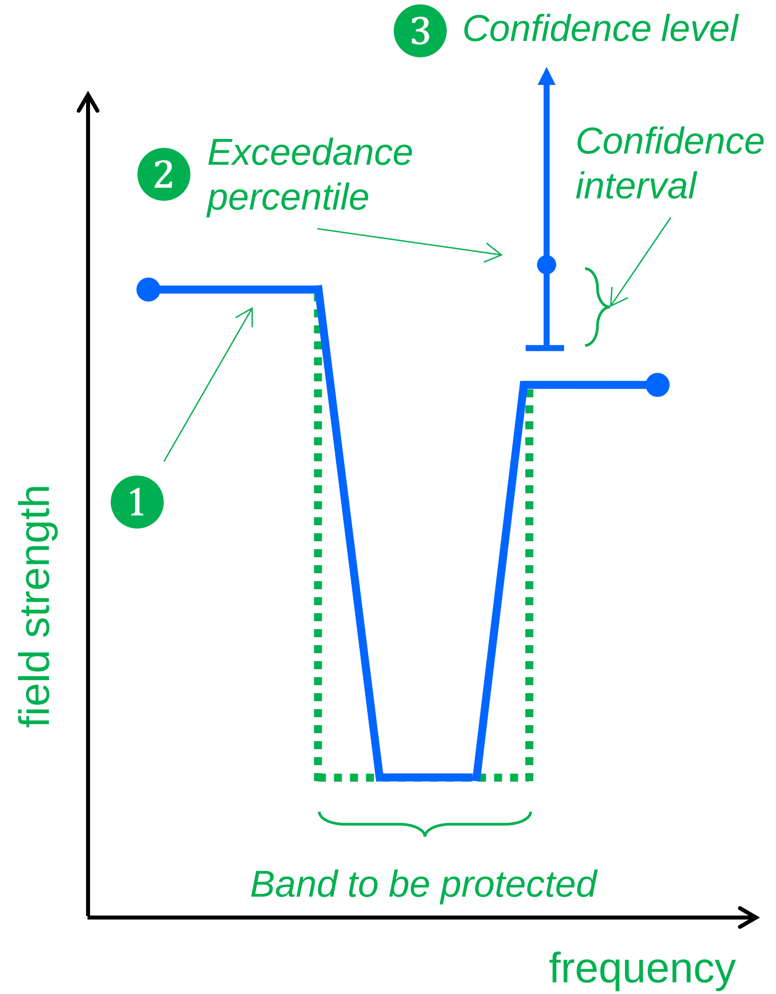
Explicit, up-front statement of the interference that systems need to tolerate before operators can bring a harmful interference claim

- Engineering proxy for the legal construct “harmful interference”

Incorporates receivers into regulation without using receiver standards

- Delegates system design decisions to operators
- Facilitates trade-offs at interference boundaries

HCT in practice



Make observations (measurements or modeling)

Construct confidence interval for the given confidence level

Decide whether to declare HCT violation or not

1. 50 dB(μV/m) per MHz
2. Exceeded at ≤ 5% of locations (95^{th} percentile)
3. At the 95% confidence level

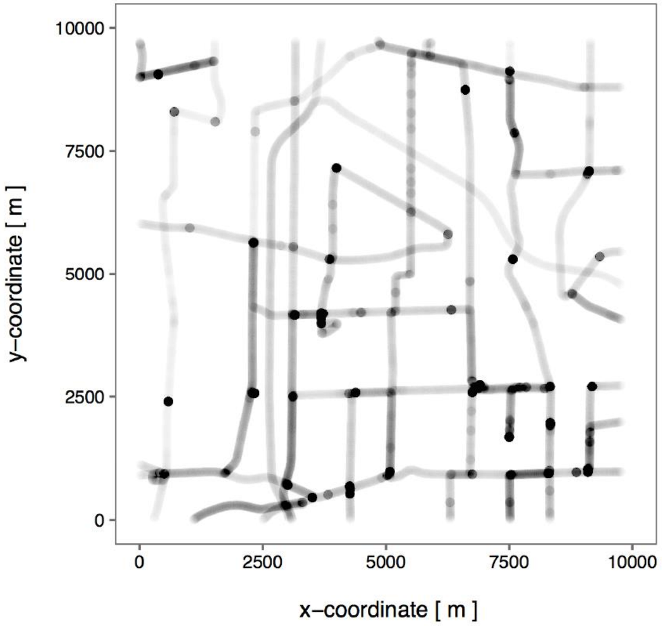
Calculating field strength from a test drive

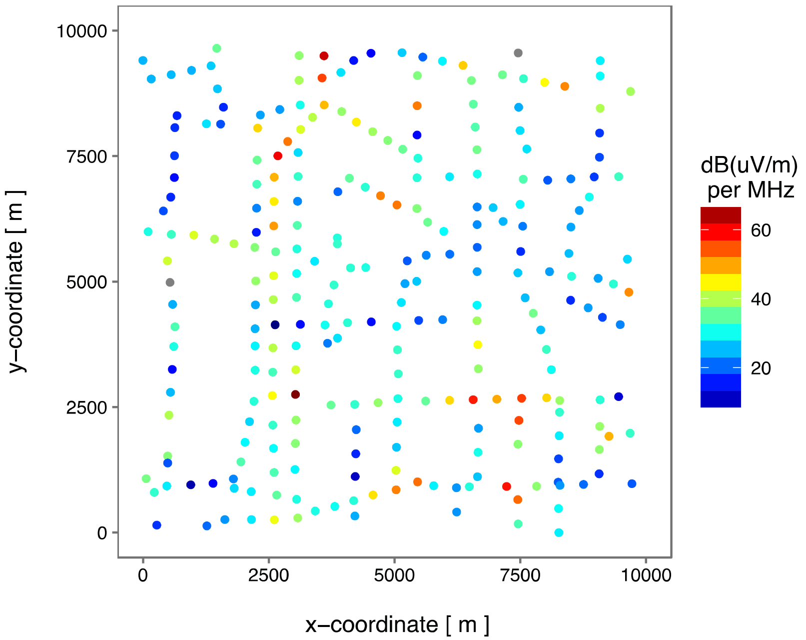
Stratification: to remove correlated measurement points, enabling fair estimation of statistical confidence

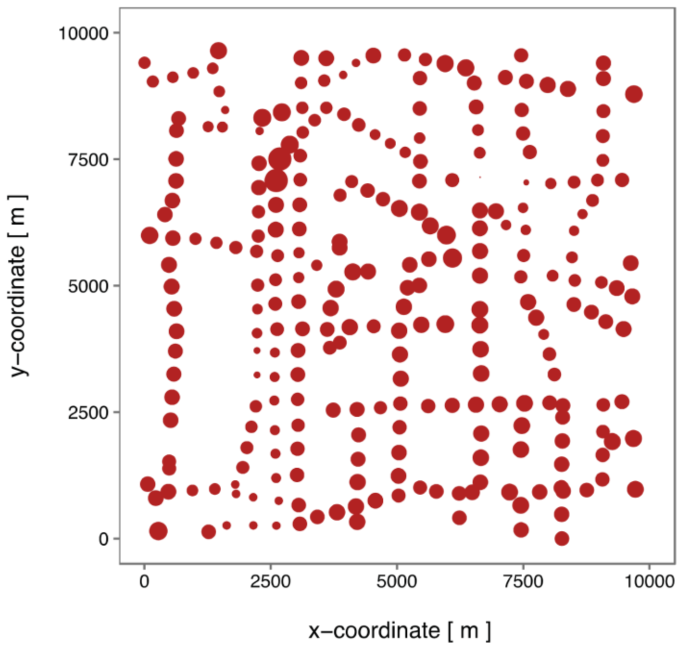
- 260 remaining samples of 65,669 from a 10 km x 10 km region → estimate within 1 dB of ground truth obtained from 4+ million samples

Weighting: ensure representativeness of measurements, giving more value to samples collected from where users are expected to be

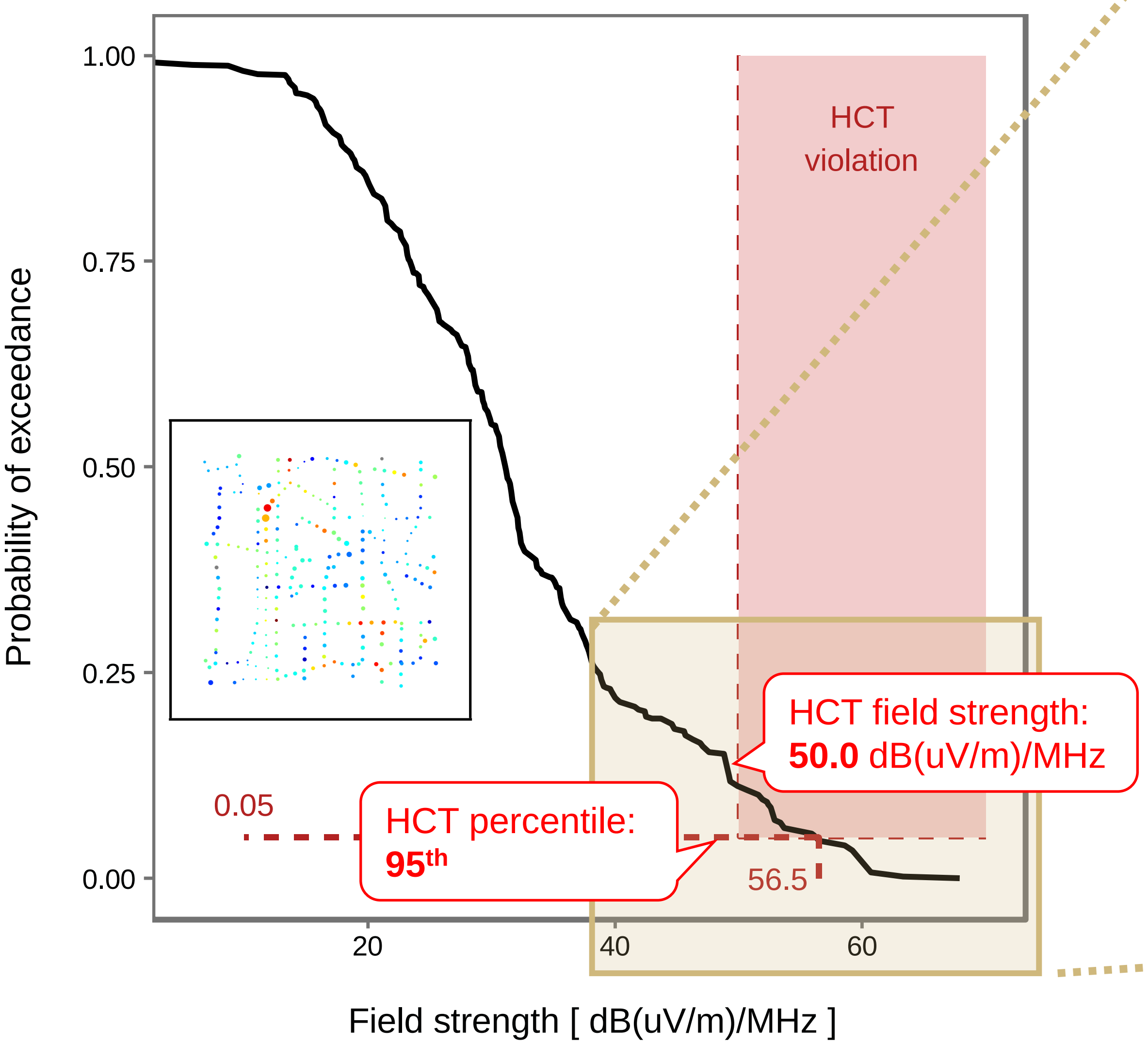
- Population density → 3 dB increase in the estimated field strength at 95th percentile







Field Strength CCDF



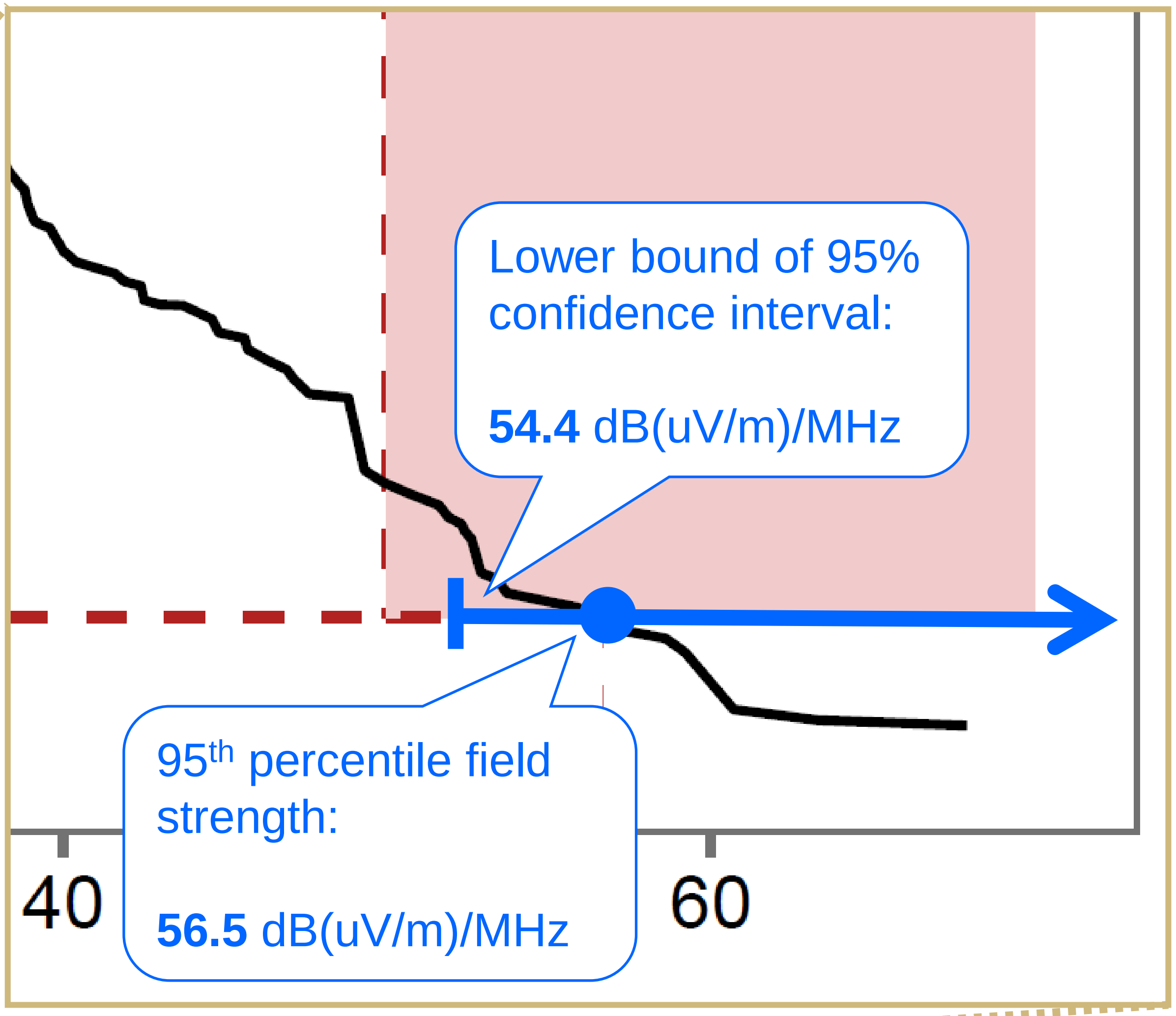


Fig. 7. Example of a grid-based method for implementin

. The population weighted and stratified CCDF from the data set of

Comparisons

Attribute	Receiver Standards	Harm Claim Thresholds	Interference Temperature
Measurement	Bench, deterministic	Field, probabilistic	Field, deterministic (?)
Neutrality	Depends on specific device and use case	Receiver device/use neutral	Device/use neutral
Goal	Ensure interference-resistant receivers	Addressing out-of-band, cross-allocation interference	Facilitate co-channel, secondary sharing
Second-party rights	N/A	Does not grant second party rights	Designed to facilitate and encourage second party, co-channel sharing
When?	At device certification	Only when there's a claim of harmful interference	Needs to be measured at all locations at all times

Summary

- Harm claim thresholds – an alternative to receiver standards

- In-band & out-of-band field strength profile
  not to be exceeded at more than some % of locations
  at some statistical confidence level
  before a system can claim harmful interference

- Simple to include in rules and measure in the field

Thank you

More in the backup slides

Backup

Research Questions

Rule definition and measurement methods for “non-cellular” scenarios

- Highly time-varying interferers
- Receiver deployments not well measured by drive tests, e.g. 3D, spatially uniform

Whether/how to incorporate modulation effects

Mapping

- HCT to EIRP transmission rules
- HCT to receiver specs (~ safe harbor)

Literature sample

FCC SPTF Interference Temperature (2002), Matheson's Electrospace (2005), Webb's Ofcom SURs (2006), Kwerel & Williams "must self-protect" (2011), De Vries & Sieh's Three Ps (2011, Probabilistic transmission permissions and receiver protections)

- Probabilistic, interference/receiver-oriented and/or field-strength approaches to RF operating permissions

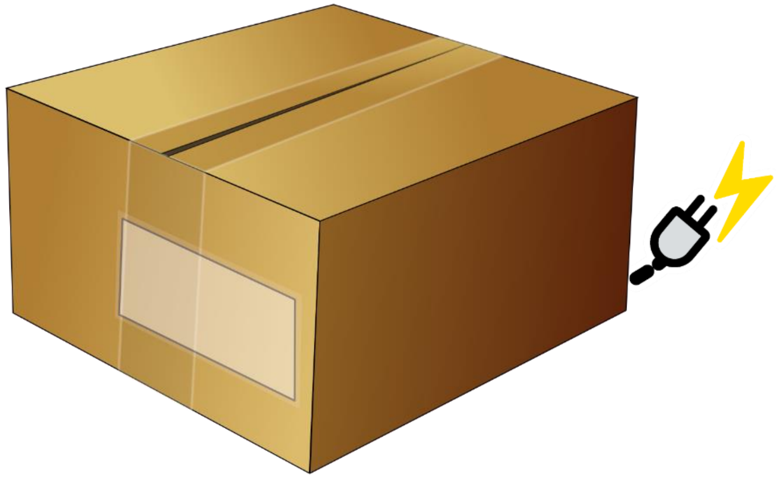
PCAST Spectrum Report (2012), FCC TAC (2013, 2014)

- Interference limits policy: "Ways to describe the environment in which a receiver must operate without necessarily specifying receiver performance"
- Harm claim thresholds: "In-band & out-of-band interfering signals that must be exceeded before a system can claim that it is experiencing harmful interference"

Riihijarvi et al. (CROWNCOM 2014, DySPAN 2017)

- Design & measurement of HCT

Results of Cardboard Box Test



Transmitter

- ✓ Transmit power
- ✓ 3 dB channel width
- ✓ OOBE mask
- ✓ PAPR
- ✓ Harmonics and spurious emissions
- ✓ …

Receiver

- x Sensitivity
- x Co-channel rejection
- x Selectivity (adjacent channel, spurious response, blocking, intermod)
- x D/U ratio
- x Dynamic range
- x …

"… the capability of a receiver to receive a wanted signal, **without exceeding a given degradation**, due to the presence of …"

Proto-HCTs in current rules

Part 27.64 (d) (2) (*2012 deal between Sirius XM and AT&T*)

- Presumed harmful interference to SDARS operations from WCS operations: "… ground signal level exceeding −44 dBm … on a test drive route, …, for more than 1 percent of the cumulative surface road distance …"

Part 96.41 (d) (1) (*3.5 GHz sharing*)

- PALs "must accept adjacent channel and in-band blocking interference … up to … −40 dBm in any direction with greater than 99% probability when integrated over a 10 megahertz reference bandwidth, with the measurement antenna placed at a height of 1.5 meters above ground level, unless …"

Design Objectives for HCTs

Straightforward to specify at a high level in rules, e.g. a small number of technology- and service-neutral parameters

Relatively easy to accommodate new technologies, e.g. by updating regulatory bulletins not changing rules

Easy to understand and apply, and in particular should not require sophisticated knowledge of statistics

- Contain as few parameters as possible
- Based on ex ante stratification distances rather than estimates derived in the course of a continuous drive test
- Enable simple estimation and planning of measurements

What the Regulator Needs to Specify

High-level parameters in regulation

- unchanging requirements, e.g. broad policy requirements like field strength, percentile and confidence level

Low-level parameters in guidance documents

- more detailed and dynamic low-level specifications, e.g. stratification distances, measurement methodologies, via
  - FCC OET Bulletins (cf. E911)
  - Delegated to standards bodies (cf. ETSI guidance on implementing EU Radio Equipment Directive)

What the Regulator Needs to Specify

Category	Parameters	Example
HCT policy	Frequency band	2 GHz
	Percentile of field strength	95th
	Field strength threshold	50 dB(uV/m) per MHz
	Confidence level	95% ($\alpha = 0.05$)
Measurement procedure	Stratification procedure	Grid-based
	Weighting method	Population weighting
	Submission of drive data	Complete without gaps
	Responsibility for processing	Claimant
	Requirements on equipment	Standard drive test
Derivation of stratification distance	Allowed methodologies	Measurements or planning tool data
	Threshold semivariance / autocorrelation	Half of saturation value (or correlation < 0.5)
	Flexibility in model choice	Exponential only

Trade-Offs in Parameter Choices

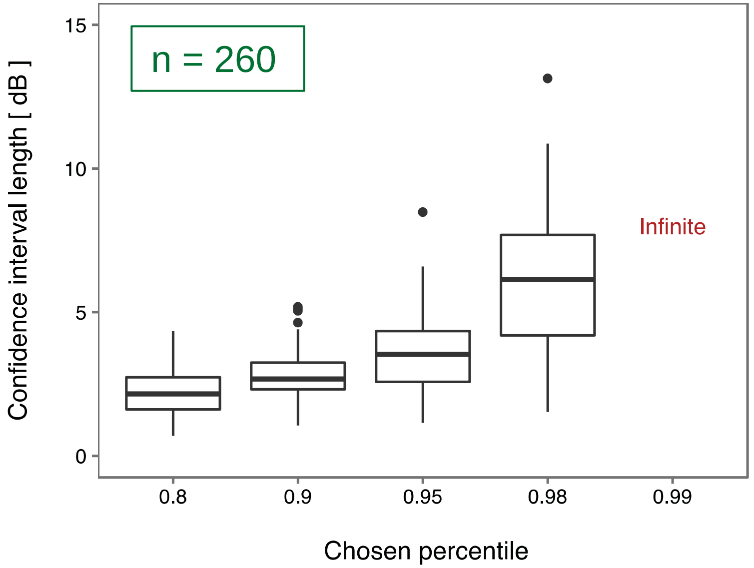
HCT percentile

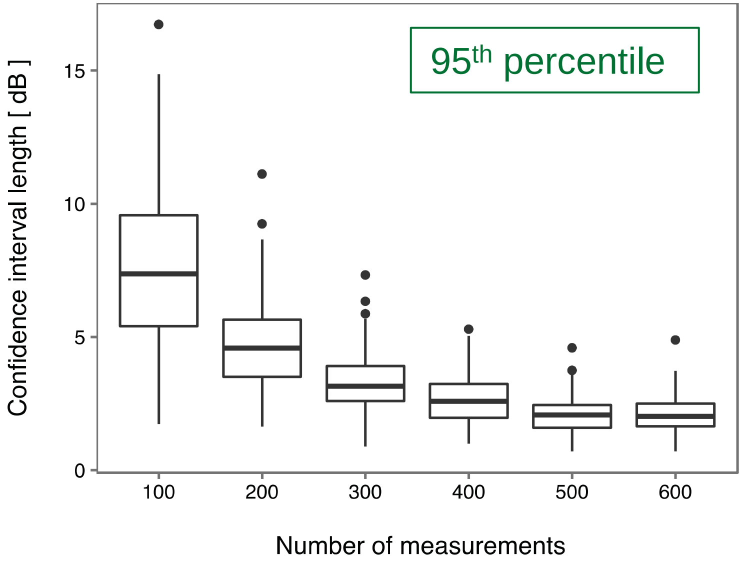
- Sweet spot ~ 95th
- Assume n=260 measurements
- Increasing HCT percentile from the 90th or 95th to 99th or higher vastly increases the amount of data needed for enforcement

Number of measurements

- Assume 95th percentile
- 200-300 measurements typically yields estimates accurate to 5 dB or better

(For given n, generated 100 samples of n measurements; plot one-sided C.I. length)





Choosing the Stratification Distance, d_S

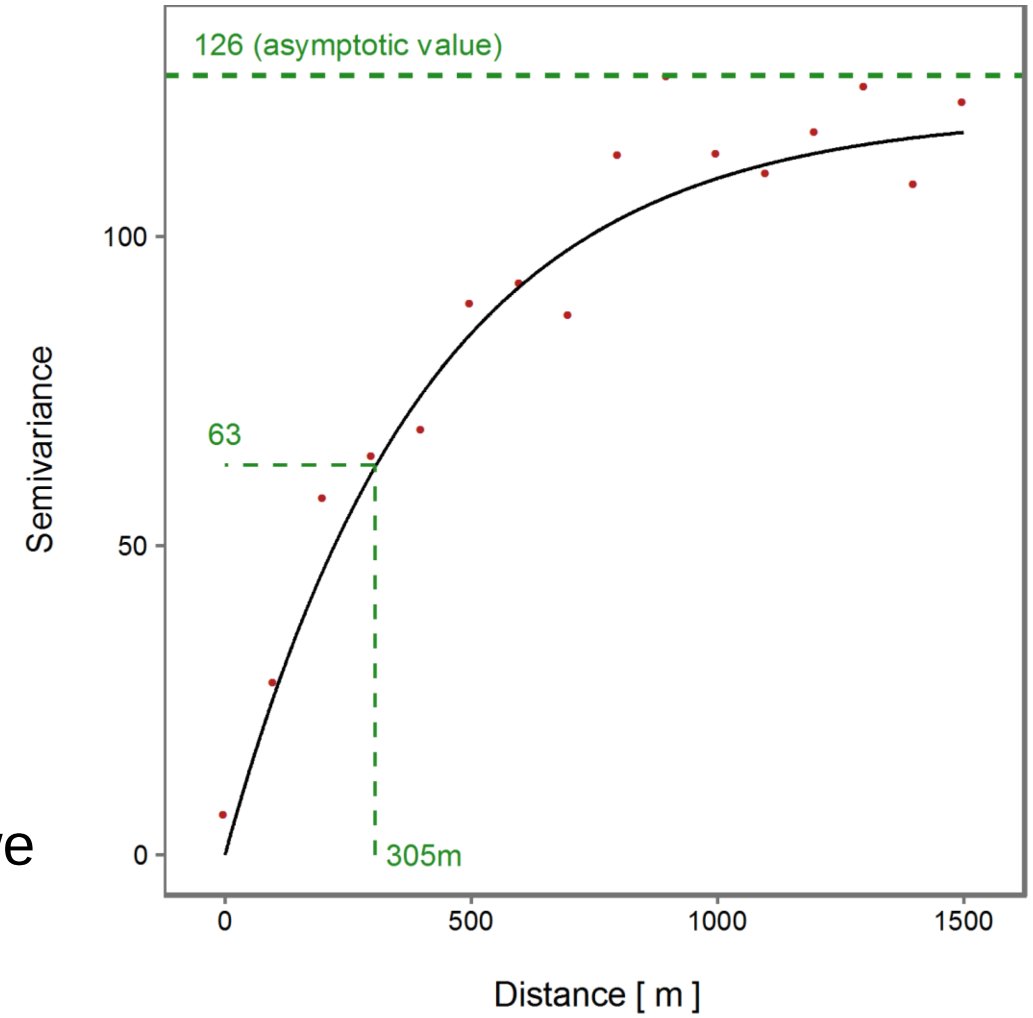
Selection of d_S a crucial choice

- Too small → spurious conclusions
- Too large distance → drives uneconomical

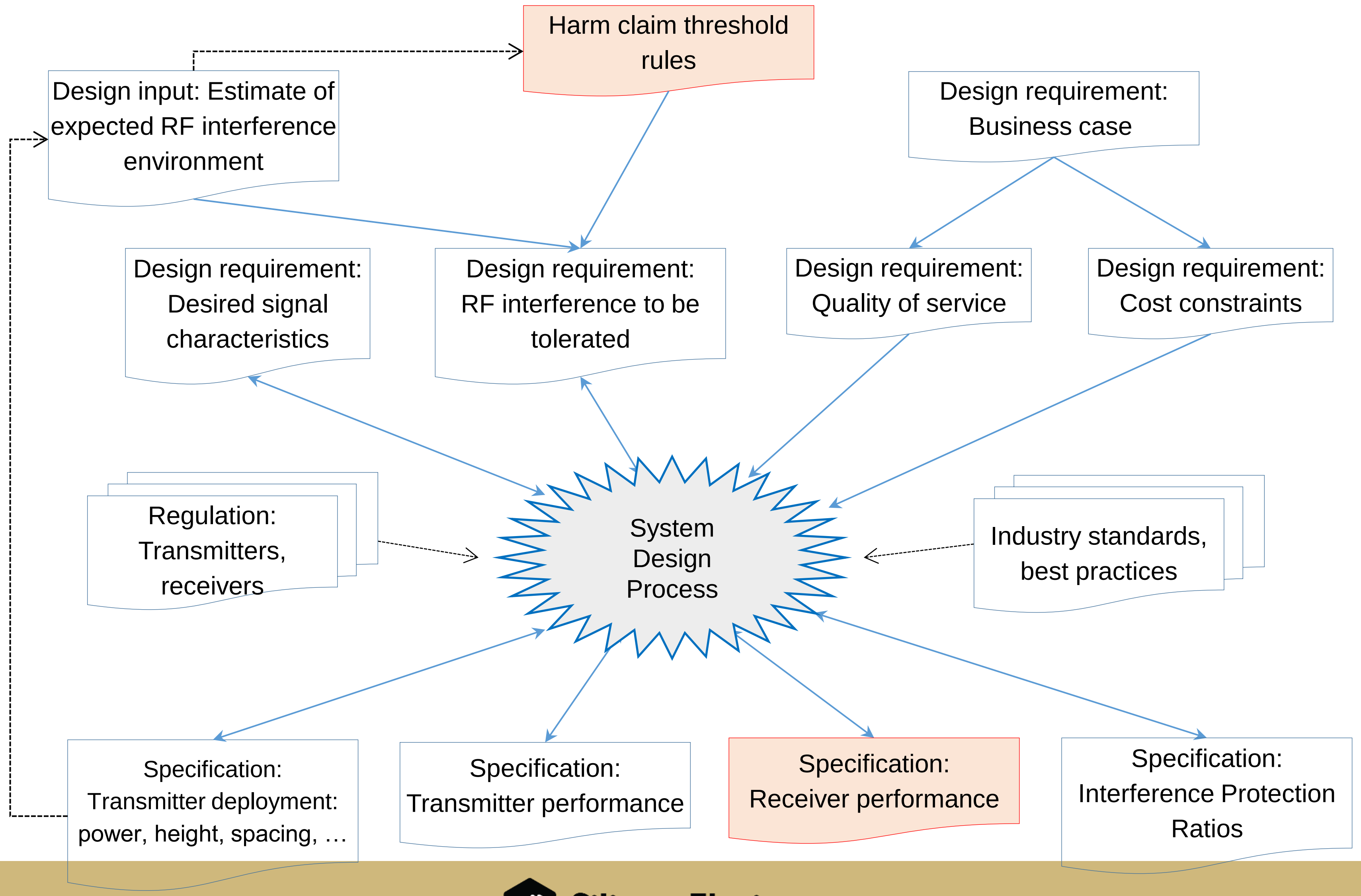
We use a simple similarity measure

- Calculate semivariogram γ(r) for all pairs in bins r ± Δ
- Fit parametric model
- Choose d_S ~ how close to asymptote

Could be derived run-time from data; we recommend fixing in advance



From harm claim thresholds to receiver performance



Benefits of Harm Claim Thresholds

Increase usage by clarifying responsibility for mitigating Harmful Interference

For Users

- Regulator delegates system design decisions, e.g. Tx vs. Rx performance
- Reduces business risk
  - Receivers: guarantee of no interference from future allocations
  - Transmitters: no harmful interference claims from poor receivers
  - Both: better estimate of deployment costs from knowing interference risks
- Increases economic efficiency: adjust Tx and Rx rights by negotiation to reach social welfare optimum

For Regulators

- Allows technology-neutral rules
- Allows future repurposing of quiet bands
- Facilitates dynamic sharing by automatic calculation of permissions

Impact of EU Radio Equipment Directive on Receivers

The Radio Equipment Directive 2014/53/EU entails new requirements on receivers that weren't in the RTTED

These are reflected in ETSI harmonized standards, e.g.

- GPS receivers are now covered
- A method to characterize UWB receivers has been developed (TS 103 361)
- A new version of EN 300 328 (2.45 GHz– Wi-Fi, Bluetooth etc.) being developed which will inter alia improve receiver performance to reject MFCN in adjacent bands (TS 103 521)
- EN 301 893 (5 GHz Wireless Access Systems / Radio LAN) now specifies receiver blocking requirements (TS 103 521)
- There are now standards for terrestrial and satellite TV receivers, and broadcast radio receivers
- Various radars (marine, aeronautical, automotive, meteorological) now subject to standardization

Session I: *Characteristics Needed in the Radio Receiver System*

Moderator

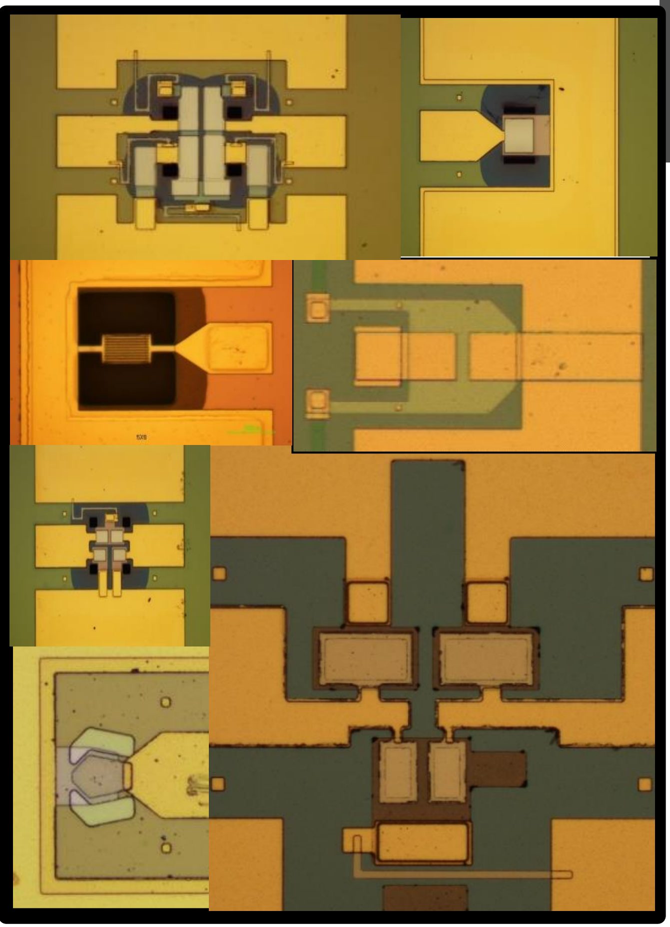
Monisha Ghosh, U of Chicago

Panelists

Paul Kolodzy, Kolodzy Consulting

Amir Mortazawi, U of Michigan

Alex Pidwerbetsky, LGS



WSRD Workshop IX

Radio Receiver Systems: R&D Innovation Needs and Impacts on Technology and Policy May 05, 2017, Arlington, VA

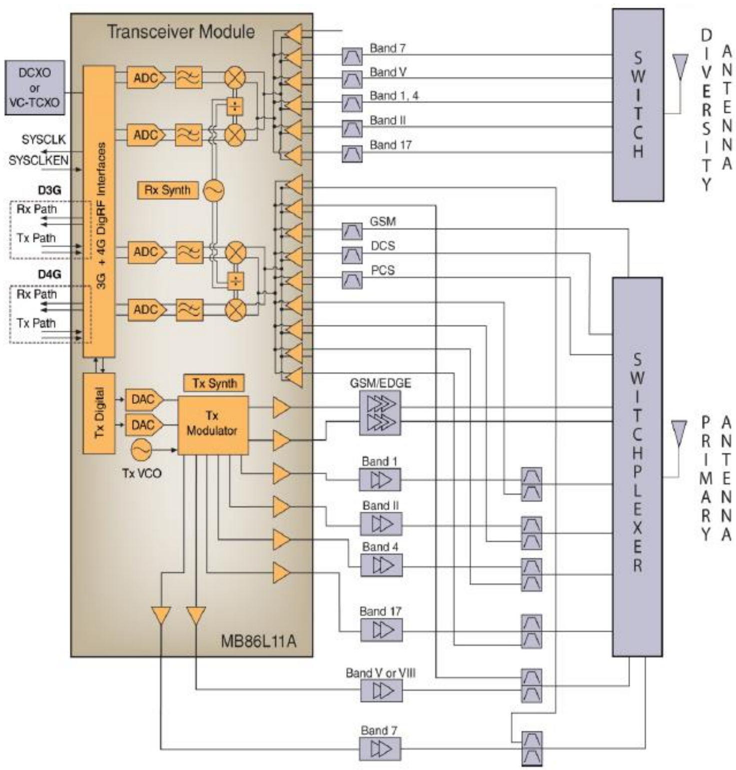
Amir Mortazawi

EECS Department

University of Michigan

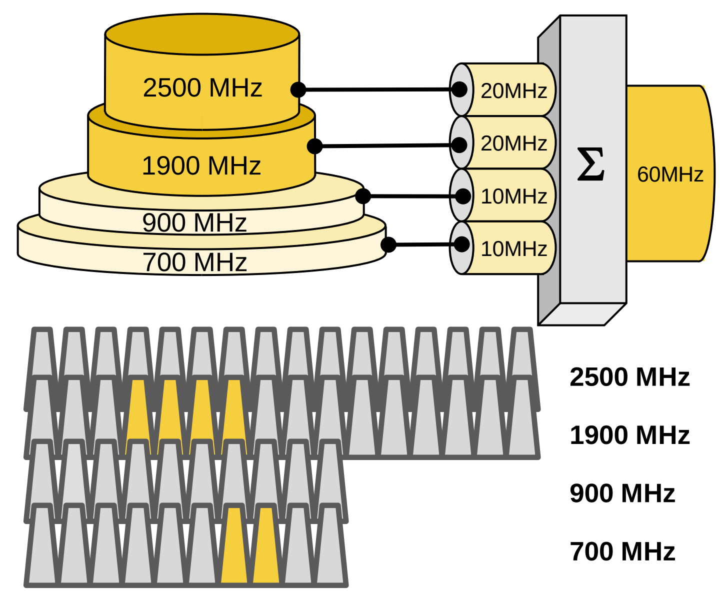
Todays’ Complex Radio Front-Ends

Multi-standard smartphones:
2G, 3G, 4G LTE, WLAN, GPS,
Bluetooth, etc.   (>20 filters)



R. Ruby, “The future of filters in cell phones,” in Microwave Symposium Digest (IMS) workshop, May 2015.

Carrier Aggregation (CA) is the summing of spectrum to enhance data throughput. Most operators have multiple frequency bands available for carrying their traffic. In normal operation, a call takes place on a single band. Carrier Aggregation allows the user to be connected to multiple bands simultaneously.



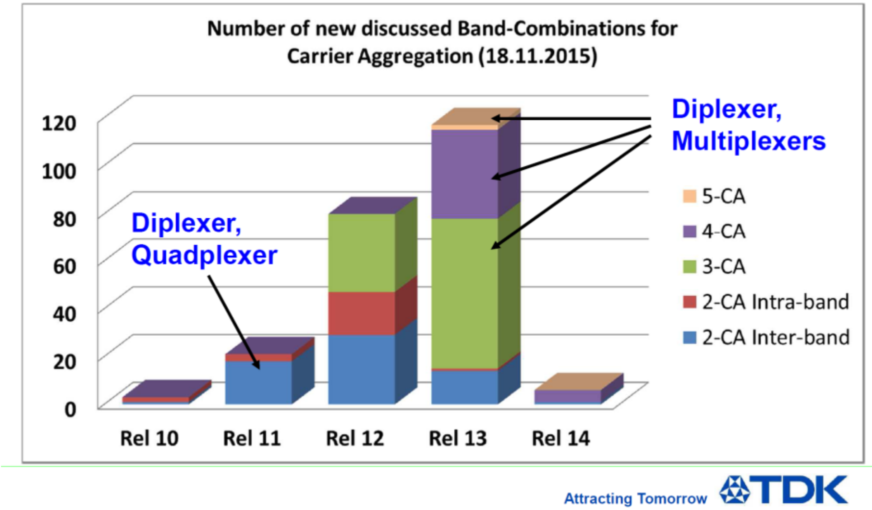
BROADCOM

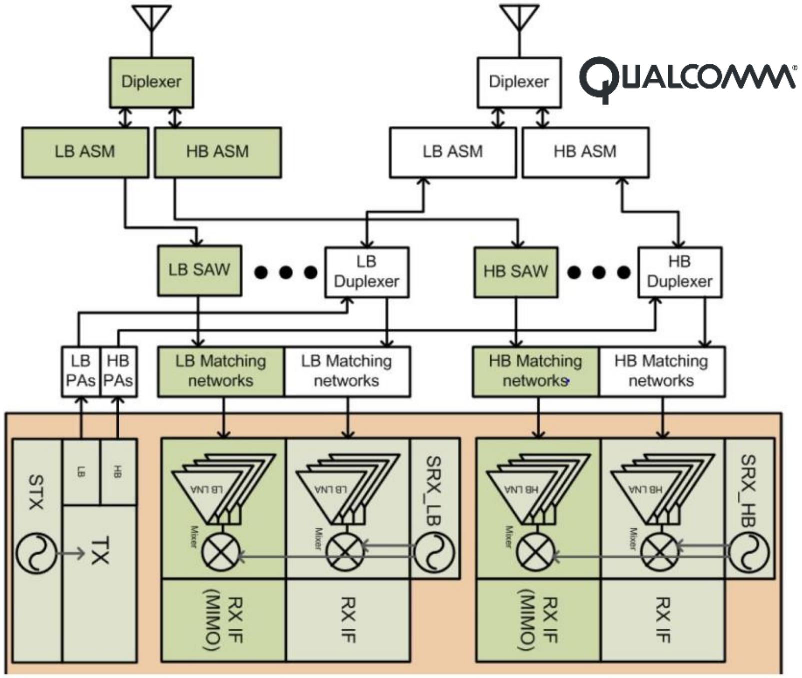
Carrier Aggregation Based 4G/5G Radios

Ever Increasing Number of carrier aggregation bands

- Aggregation across diverse spectrum types for best use of spectrum, FDD, TDD
- MIMO: More antennas to increase spectral efficiency
- Number of carrier aggregation bands is increasing
- In 4G and 4.5G max 5-CA is allowed, in 5G there is no limit
- Multiple Simultaneous receive chains to support carrier aggregation and MIMO Drastically increase Transceiver complexity
- RF Front-End Insertion loss challenge

CA-Band Combinations: Constantly increasing …





There is a Clear Need for Techniques to Reduce Radio Front-End Complexity

Session II: *Radio Receiver System Technology R&D*

Moderator

Jenshan Lin

Panelists

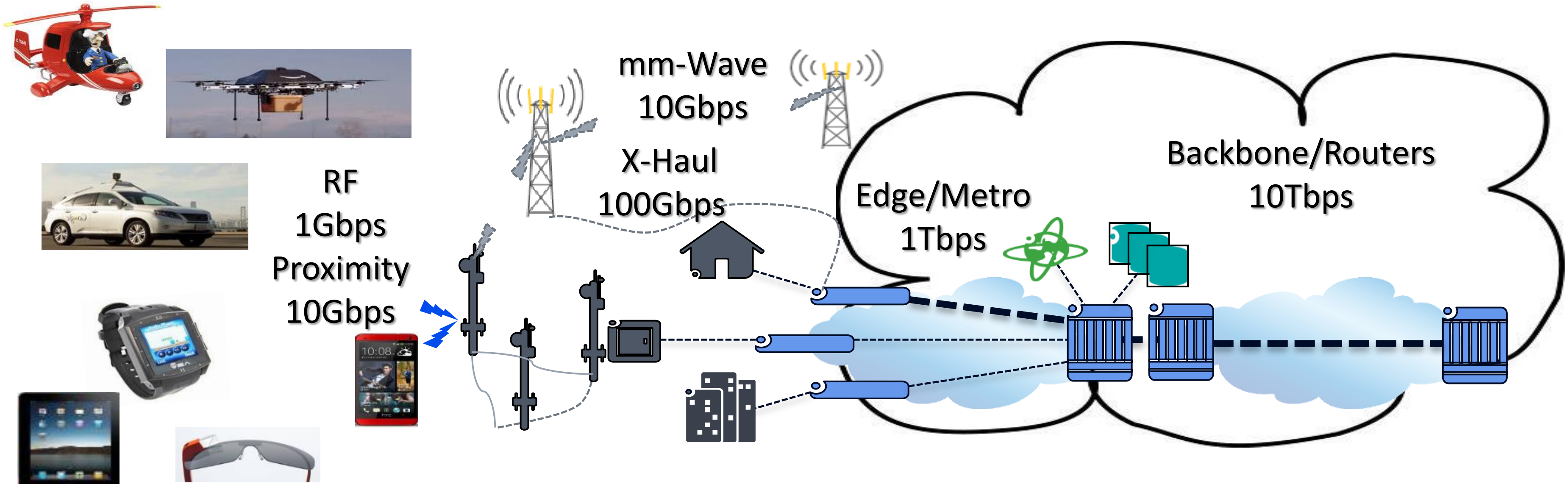
Young-Kai Chen, Nokia Bell Labs

Howard McDonald, DISA

Xiaoli Ma, Georgia Tech

Vision of Mobile Network Evolution @ 2020

Typical Interface	Terminal	Front-Haul / x-Haul
2017	< 0.1G	2.5G / 10G
2020	1G / 10G	100G / 1 T



NOKIA Bell Labs

Example of Envisioned 5G Infrastructure for 2020

Capacity

- Air Interface
- Multipoint, Multi Antenna System Design
- Spectrum & Infrastructure Sharing
- mm-wave Bands

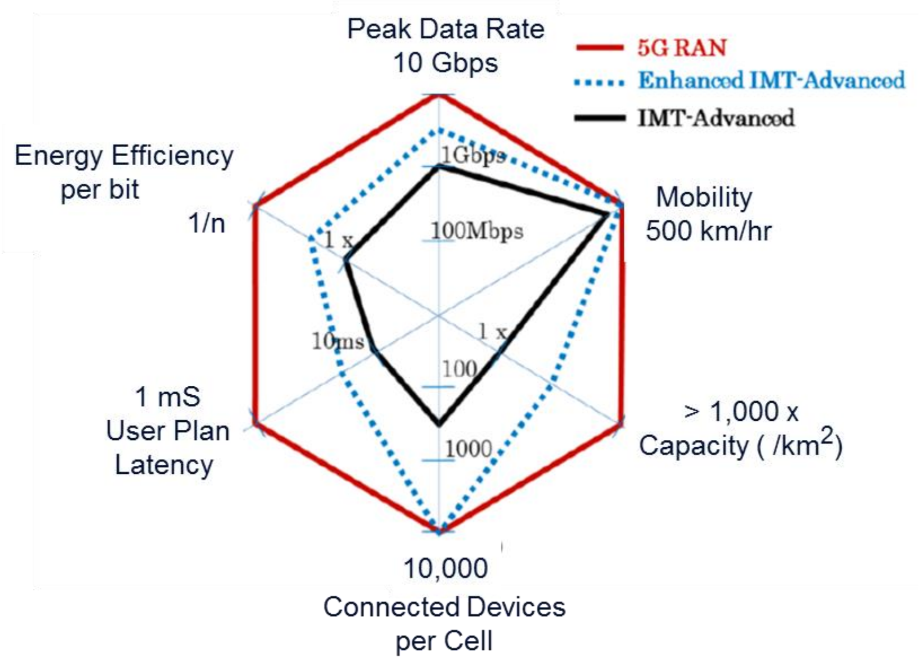
Connectivity

- Channel adaptation
- Interferences
- Smart nodes

Networking and Applications

- Networking & cloud-based architecture
- Latency, security, reliability
- Service Framework, Energy efficiency

Vision of 5G Performance



Source: 5GMF Whitepaper

NOKIA Bell Labs

Capacity

Bandwidth and spectral efficiency

- New multiple access scheme and waveforms (e.g. IDMA, NOMA, FB-OFDMA)
- Carrier aggregation (e.g. channel bonding, spectrum auction, white space)
- Spatial signal processing (e.g. MIMO, AI)
- New frequency bands (e.g. mm-wave)

Technology needed:

- Wideband/multi-band receiver (e.g. wideband tunable RF ICs, filters)
- Advanced antenna (e.g. Metamaterial, MEMS, Fractural…)
- Low power semiconductor SoC

Connectivity

Air Interface

- Channel adaptation (e.g. IDMA, NOMA, full duplex)
- Interferences (e.g. CoMP, Adaptive Beam Former)
- Smart nodes (e.g. MIMO, AI)

Technology needed:

- Channel sounding (e.g. high dynamic range wideband RF sensors)
- Interference management (e.g. CoMP, tunable RF filters, active cancellation)
- Novel smart MAC (e.g. low power AI, application-driven)

NOKIA Bell Labs

Need More Advanced Receiver Technologies
- Some examples:

Physical Radio Devices

- Low latency MIMO processor and MAC
- Wideband receiver with spectrum sensing
- Tunable band-pass and notch filters
- Interference cancellation techniques
- Energy efficient beam former and processors
- mm-wave IC with integrated antenna array

Air Interface

- Cognitive radio network and channel adaptation
- Advanced interference cancellation and mitigation
- Embedded security

Radio Access Nodes

- Advanced waveforms for heterogeneous traffics
- Aggregation of UEs, IoTs, data, mm-wave…
- Prioritize various demands on latency, capacity, etc.
- Localized distributed RAN and artificial intelligence

Radio Access Network

- Dynamic/predicative service provisions adapting to prioritized requests in capacity, latency and emergency
- Integrated data storage and switch for content buffers
- Network abstraction for SDN and NFV

NOKIA Bell Labs

Radio Receiver Systems: R&D Innovation Needs and Impacts on Technology and Policy

Xiaoli Ma

Acknowledgments: Dr. Wei Zhang, Dr. Qi Zhou, Dr. Benjamin Hamilton,
Dr. Giwan Choi, Dr. Jiaxi Xiao, Dr. Malik Usman Gul,
Dr. Brian Beck, Qingsong Wen, Yiming Kong

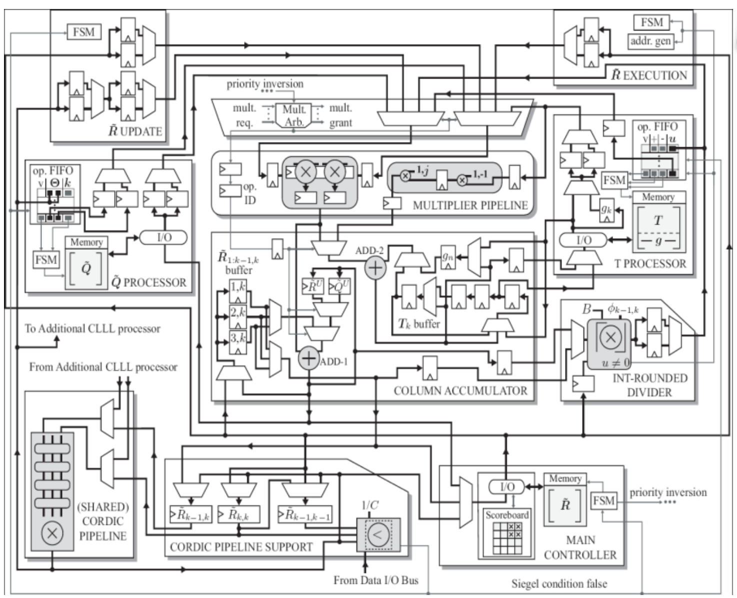
ARO, NSF, NI, AFRL

One Dilemma

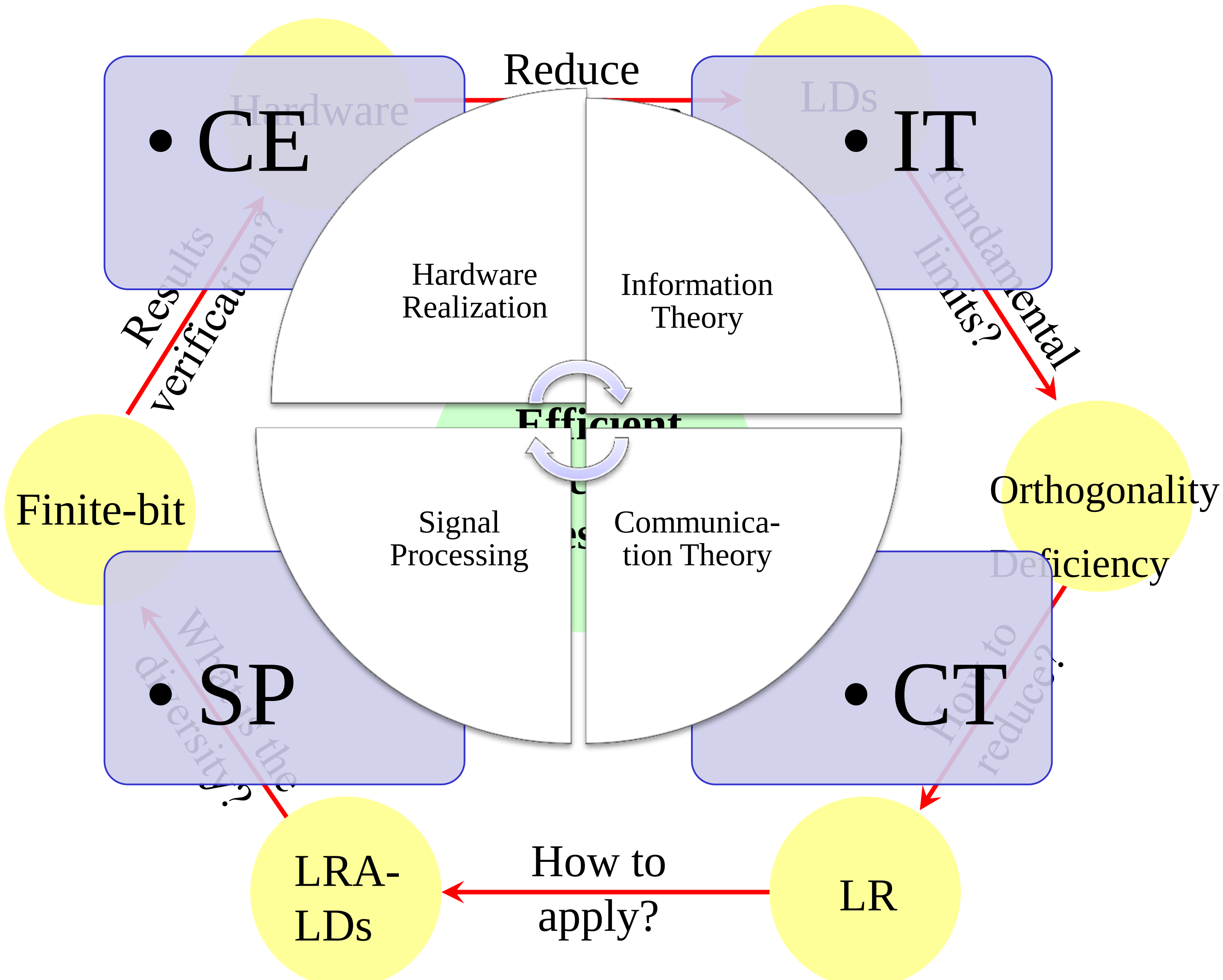
What we know is not what we use

What we use is not what we know

```
INPUT: H , δ ? (1/2, 1); OUTPUT: Q̃ , R̃ , T
[Q̃ ,R̃ ,T ] = sorted QR (H );
k = 2 ;
while k ≤ m
    for n = k − 1 : −1 : 1
        u = round ((R̃ n,k / R̃ n,n ));
        if u ? = 0
            R̃ 1:n,k = R̃ 1:n,k − u · R̃ 1:n,n ;
            T:,k = T:,k − u · T:,n ;
        end
    end
    if δ|R̃ k−1,k−1|^2 > |R̃ k,k |^2 + |R̃ k−1,k |^2
        Swap the (k-1)th and kth columns in R̃ and T
        Θ = [α? β; −β α]  where α = R̃ k−1,k−1 / ||R̃ k−1:k,k−1||;
                                β = R̃ k,k−1 / ||R̃k−1:k,k−1||;
        R̃ k−1:k,k−1:m = Θ R̃ k−1:k,k−1:m ;
        Q̃ :,k−1:k = Q̃ :,k−1:k Θ^H ;
        k = max( k − 1, 2);
    else
        k = k + 1 ;
    end
end
```



Methodology



Session III: *Implementation and Adoption of Radio Receiver Technologies*

Moderator

Michael Ha

Panelists

Don Witters, FDA

Michael Fitton, Intel

Bob Pavlak, FCC

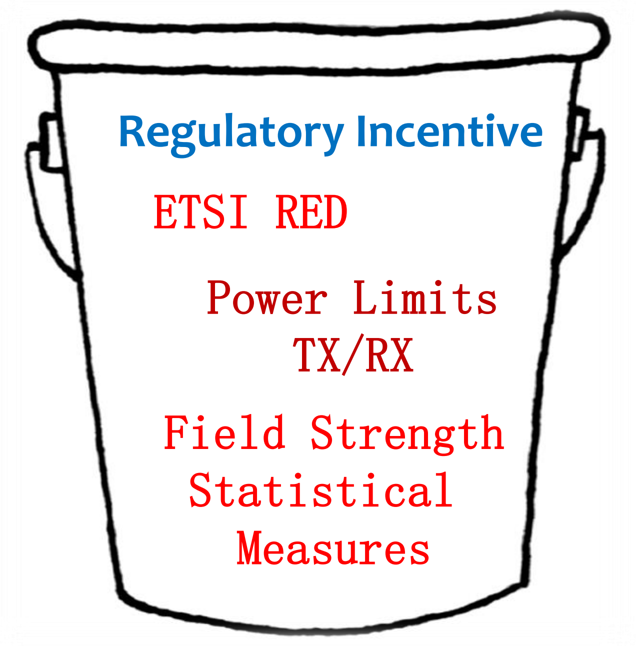
Industry Driven
Cost vs. Performance
RF Selectivity
Poor Receiver Design
Safety of Life
Receiver Characteristics
Performance Degradation
Receiver Overload
ITU
Transmitter vs. Receivers
Non-Linearity
Public Safety
ETSI RED
LNA Compression
SDR Dynamic Range
Jammers
Cognitive Radio
Interference Temperature
IEEE
FCC Regulation
Performance Requirement
Best Practice Guide
Filters
3GPP Receiver Standard
Dynamic Range
One-Size Fits All
HSM
Coordination
WiFi Coexistence
GPS Receivers
Military Receivers
Certification Process
Digital Diplexer
Harm Claim Threshold
Transmitter vs. Receivers
Temporal/Spatial
High Power Radar
Low Power Unlicensed

Session III: Implementation and Adoption of Radio Receiver Technologies

What do we want?

How do we execute?

Where can regulators help?

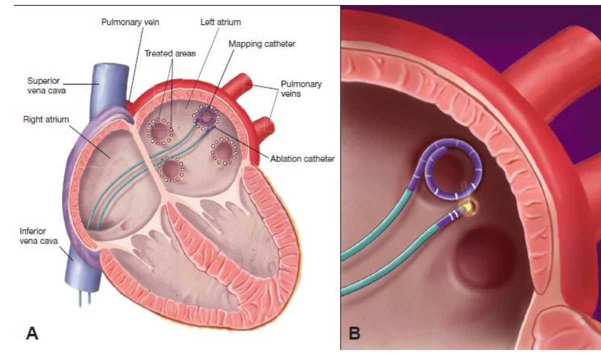


CDRH, FDA protects public health by assuring medical device safety and effectiveness, and radiological health

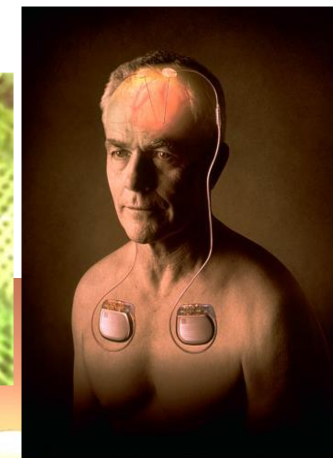
- Medical device: prevent, diagnose, treat, cure disease, affect body structure, implants, and in vitro products and reagents.
  - U.S. market >175,000 medical devices, 18,000 manufacturers
  - Wireless medical devices: thermometers, implantable cardiac pacemakers/ICDs, robotic surgery, monitors, lab equip., X-ray/CT, MRI, diathermy, hyperthermia
  - Bluetooth, Wi-Fi, MedRadio (MICS), WMTS, RFID, Ultra-wideband, MBAN, NFC, Cellular, LF inductive

Wireless Medical Devices

Wireless technology for imaging & treatment



Wireless for telemetry, programming, control



U.S. FOOD & DRUG ADMINISTRATION

Tools/Challenges for Wireless Devices

- Regulation and guidance:
  - 1976 Medical Device Amendments
  - 1968 Radiation Control Act for Health & Safety
  - Radio Frequency Wireless Technology in Medical Devices - Guidance for Industry and Food and Drug Administration Staff
- AAMI Technical Information Report AAMI TIR69:2017: Risk management of radio-frequency wireless coexistence for medical devices and systems
- ANSI C63.27 Draft Standard for Evaluation of Wireless Coexistence (expected publication late spring)
- **Challenges:** awareness by, and of, other wireless emitters, spectrum competition, coexistence, security, EMC of the wireless signals

Summary Panel

Moderator

John Chapin, Roberson & Assoc.

Panelists

Monisha Ghosh

Jenshan Lin

Michael Ha

Closing Remarks

Slides will be posted on the Workshop Website

https://www.nitrd.gov/nitrdgroups/index.php?title=WSRD_Workshop_IX

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