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NSC-01 Recommended Practice for Co-existence between Tactical Data Links and Electronic News Gathering Systems

MIL-CIV TDL ENG TASK GROUP

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Scope

This Specification provides Recommended Best Practices for spectrum sharing between current and future Tactical Data Links (TDLs) and Electronic News Gathering (ENG) Systems in the 2025-2110 MHz of Spectrum. The Specification establishes the metrics, criteria and recommended practices for acceptable sharing of spectrum between these systems. It provides methods, procedures and controls needed to enable automated dynamic spectrum access for TDLs to operate on a co-primary, non-harmful interference basis with the incumbent ENG systems.

Purpose

This document enables the proliferation of best practices for automated spectrum access, spectrum co-existence and interference management between current and future Tactical Data Links (TDLs) and Electronic News Gathering (ENG) Systems in the 2025-2110 MHz of Spectrum. This enables users of TDLs and ENG systems, as well as regulatory bodies to gain confidence and facilitate wider adoption of automated spectrum sharing across these systems.

There is a need to establish metrics, criteria, and best practices for acceptable sharing of spectrum between DoD and commercial entities. There is a need to develop methods, procedures, and controls needed to enable greater access to spectrum sharing across the Military-Civilian divide. Current sharing practices are based on mitigating interference in a largely manual process of interaction among operational, transitioning, and incumbent systems. In particular, current spectrum sharing policy recommends conservative interference contours (exclusion zones) that use a conservative propagation prediction to ensure minimal interference to the operation of incumbent systems. This kind of interference-avoidance-based approach by its very nature results in a rather poorly utilized spectrum on a spatio-temporal basis. The goal of the MIL-CIV Spectrum Sharing Recommended Practice as it applies to TDL-ENG is to help create a guideline for broader efficient shared spectrum usage. As part of this guideline, it is also important for us to clarify terms such as “Co-Primary” as applicable to this specific context. Other considerations include very low thresholds for interference on the commercial side which makes it difficult to share spectrum. As an example, in the 2025-2110 MHz band, interference power above -108 dBm is not considered acceptable, even though this is well below the noise floor. This may result in DoD having to cease operations entirely in a given geographic area. Therefore, this Task Group (TG) was created by the National Spectrum Consortium (NSC) to develop innovative recommendations for efficient spectrum sharing that will help initiate the dialogue with the DoD, ENG Operators, and regulators of the spectrum.

List of Participants

MIL-CIV Task Group Voting Members (At the Time of Project Completion)

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Executive Summary/Overview

National management of radio frequencies is typically divided between government use of spectrum (for National Security, Public Safety and critical infrastructure purposes) and commercial use of spectrum for business related activities. Regulatory authorities implement statutory frequency resource objectives through various mechanisms. In the United States, Federal Departments and Agencies coordinate their use of spectrum bands through the Department of Commerce's National Telecommunications and Information Administration (NTIA).

The finite nature of spectrum has led to a need to dramatically improve spectral efficiency to unleash the full potential societal value of the resource. This presents challenges for government and companies that for decades have counted on exclusive access to fixed blocks of spectrum. This has led to governance decisions that allowed compatible activities to share given spectrum blocks. For the most part, spectrum deconfliction consisted of relatively static mechanisms to allow secondary spectrum use in a given band as long as that use would not interfere with the primary license. This approach improved the number of supported spectrum dependent systems but reached a practical limit driven by the challenges associated with more granular coordination required to implement 'dense packing' of spectrum dependent systems in a given area.

Objectively, the incorporation of dynamic spectrum sharing as an element of system design will greatly reduce the amount of spectrum that at any given time goes unused. Dynamic Spectrum Access (DSA) allows the host radio to utilize and share available spectrum in the most efficient manner possible while minimizing or eliminating interference to other users in the band. These systems, however, require significant technical coordination throughout the lifecycle of spectrum dependent systems. While there has been a degree of success among homogeneous systems and systems with strong technical and program governance over the lifecycle of user equipment, in most cases interagency, government and commercial spectrum deconfliction continues to rely on static mechanisms to coordinate use.

Traditional approach to avoid interference is to create an exclusion/protection zone around the victim receiver in the area where a transmitter may cause interference above a certain level to the said receiver. This approach suffers from a few issues. First, it assumes that the receiver is active 100% of the time, and therefore any transmitter will have to avoid transmitting while in the area 100% of the time, which may be overly pessimistic. Secondly, this approach either assumes that the receiving antenna pointing direction is known a-priori or that the direction changes dynamically in short timescales, thus effectively making it a high-gain omnidirectional antenna. These constraints have the potential for the Department of Defense (DoD) to waste spectrum in both time and space. One sensing-based DSA solution works on the principle of sensing the signal to be protected. If DSA detects the victim signal, then any transmitter that may cause interference to the receiver may be switched to a different frequency. This approach eliminates both temporal and spatial waste of the geographic approach, as the DSA system will only turn off if the victim signal is actually present. However, this approach may not always protect the victim receiver because of the hidden node problem. A second sensing-based DSA solution uses a beacon signal at the victim receiver, which turns on when the victim receiver is active. This approach requires modifying the victim receiver hardware, and both approaches rely heavily on the fidelity of the sensing hardware. Other approaches including databases, among others have their own limitations, especially when the RF environment is changing rapidly, and mobility is involved.

The Defense Information Systems Agency's Defense Spectrum Office (DISA-DSO) has proposed and developed a Spectrum Management Coordination Portal (SMCS) to be used for coordination

between the TDLs wanting to use this spectrum and the Broadcast system having incumbent operations in this band. It has been proposed that operators of the Broadcast systems such as ENG, need to register into the SMCS Portal and inform the database of its current use, or planned usage.

The goal of the Military-Civilian (MIL-CIV) Spectrum Sharing TG is to develop effective, reliable and innovative spectrum sharing approaches between the DoD Tactical Data Links and commercial Electronic News Gathering systems in the 2025–2210 MHz band, that enable less restrictive yet reliable forms of spectrum sharing with resulting higher spectral efficiency (bit/s/Hz/km²); and/or decrease the geographic proximity of Spectrum Dependent Systems (SDSs) over time. In this report, we describe a number of DSA and non-DSA based solutions to this problem, and evaluate their individual pros and cons. Then, we provide our recommendations based on current technology and future direction.

Acronyms

| | |
|----------|--------------------------------------------------------------|
| ACTS | Air Combat Training Systems |
| AFC | Automated Frequency Coordination |
| AOI | Area of interest |
| APIs | Application Programming Interfaces |
| ATPC | Automatic transmitter power control |
| ATSC | Advanced Television Systems Committee |
| AWS | Advanced wireless services |
| BAS | Broadcast Auxiliary Service |
| CBRS | Citizens Broadband Radio Service |
| CEPT | Conference of Postal and Telecommunications Administrations |
| C/I | Carrier-to-interference ratio |
| CIRN | Cooperative Intelligent Radio Network |
| COI | Community of interest |
| DFS | Dynamic Frequency Sharing |
| DISA-DSO | Defense Information Systems Agency's Defense Spectrum Office |
| DoD | Department of Defense |
| DoS | Denial of service |
| DRL | Data Return Link |
| DSA | Dynamic Spectrum Access |
| DSS | Dynamic spectrum sharing |
| DVB-T | Digital Video Broadcasting-Terrestrial |
| ENG | Electronic News Gathering |
| ESC | Environmental Sensing Capability |
| EZ/PZ | Exclusion Zone / Protection Zone |
| FCC | Federal Communications Commission |
| FDD | Frequency Division Duplex |
| FFT | Fourier transform |
| GOES | Geostationary Operational Environmental Satellite |
| HCLOS | High-Capacity Line-of-Sight |
| HRV | High Resolution Video |
| IIC | Incumbent informing capability |
| IoMT | Internet of Military Things |
| IPC | Interference protection criteria |
| JTRS | Joint Tactical Radio System |
| LBT | Listen-before-Talk |
| LHCP | Left-Hand Circular Polarization |
| LPI | Low Probability of Intercept |
| LSA | Licensed Shared Access |
| LTE | Long-Term Evolution |
| MIL-CIV | Military-Civilian |
| MIMO | Multiple-Input Multiple-Output |
| MMSEC | Minimum Mean Square Error Combining |
| MRC | Maximal Ratio Combining |
| NAB | National Association of Broadcasters |
| NASA | National Aeronautics and Space Administration |
| NOAA | National Oceanic and Atmospheric Administration |
| NSC | National Spectrum Consortium |
| NTIA | National Telecommunications and Information Administration |

| | |
|-------|-------------------------------------------|
| NWS | National Weather Service |
| OAP | Optimal Adaptive Polarization |
| OPSEC | Operational security |
| PDL | Polarization Dependent Loss |
| PIM | Passive intermodulation |
| PMD | Polarization Mode Dispersion |
| POES | Polar Operational Environmental Satellite |
| PUE | Primary User Emulation |
| RATs | Radio Access Technologies |
| RFSA | RF Situational Awareness |
| RHCP | Right-Hand Circular Polarization |
| RIC | RAN Intelligent Controller |
| SAS | Spectrum Access System |
| SCS | Spectrum Coordination System |
| SDR | Software defined radio |
| SDSs | Spectrum Dependent Systems |
| SGLS | Space Ground Link System |
| SINR | Signal to Interference plus Noise Ratio |
| SIR | Signal-To-Interference Ratio |
| SMCS | Spectrum Management Coordination Portal |
| SOI | Signal of Interest |
| SPD | Switched Polarization Diversity |
| SRW | Soldier Radio Waveform |
| SSRA | Spectrum support risk assessment |
| TDD | Time Division Duplex |
| TDLs | Tactical Data Links |
| TDRSS | Tracking Data and Relay Satellite System |
| TG | Task Group |
| TO | Transmission Operator |
| TRR | Tactical Radio Relay |
| TSG | Technology and Standards Group |
| WNW | Wideband Networking Waveform |

1. Background of the Problem

Wireless broadband represents a critical component of economic growth, job creation, and global competitiveness because consumers are increasingly using wireless broadband services to assist them in their everyday lives. Demand for wireless broadband services and the network capacity needed to support those services is surging, resulting in a growing demand for spectrum. Similarly, the number and type of devices being used by consumers to access content over wireless broadband networks have significantly increased. These trends are resulting in more demand for network capacity and for more investment of capital in the infrastructure, technology, and spectrum. The increase in demand for wireless spectrum, moreover, is expected to continue [1].

Both Congress and the President have recognized the importance of wireless broadband to the national interest. In 2009, Congress directed the Federal Communications Commission (FCC) to develop a National Broadband Plan to ensure that every American has access to broadband capability. The National Broadband Plan [2], released in 2010, recommended that the FCC make 500 MHz of spectrum newly available for broadband use within the next 10 years, of which 300 MHz of spectrum between 225 MHz and 3.7 GHz should be made newly available for mobile use within five years. The National Broadband Plan recognized that to achieve this goal, some of this spectrum would come from spectrum allocated for Federal use. It recommended that NTIA, in consultation with the FCC, conduct an analysis of the possibility of reallocating a portion of the 1755-1850 MHz band, which is adjacent to the AWS-1 uplink/mobile band at 1710-1755 MHz and currently allocated for Federal use, to pair with the 2155-2175 MHz band, which is currently allocated for services that support commercial use.

On June 28, 2010, a Presidential Memorandum entitled “Unleashing the Wireless Broadband Revolution” [3] was released. The 2010 Presidential Memorandum stated that “America’s future competitiveness and global technology leadership depend, in part, upon the availability of additional spectrum.” The memorandum stressed that there are few technological developments that hold as much potential to enhance America’s economic competitiveness, create jobs, and improve the quality of our lives as wireless high-speed access to the Internet. Expanded wireless broadband access will trigger the creation of innovative new businesses, provide cost-effective connections in rural areas, increase productivity, improve public safety, and allow for the development of mobile telemedicine, telework, distance learning, and other new applications that will transform American’s lives. The memorandum also stated that spectrum and the new technologies it enables are essential to the Federal Government, which relies on spectrum for important activities, such as emergency communications, national security, law enforcement, aviation, maritime, space communications, and numerous other Federal functions. It further stated that spectrum is also critical for many state, local, and tribal government functions. The 2010 Presidential Memorandum directed NTIA to collaborate with the FCC to “make available a total of 500 megahertz of Federal and non-Federal spectrum over the next ten years, suitable for both mobile and fixed wireless broadband use.”

On June 14, 2013, another Presidential Memorandum was released entitled, “Expanding America’s Leadership in Wireless Innovation” [4] stating that although existing efforts will almost double the amount of spectrum available for wireless broadband, efforts must be made to free up even more spectrum and create new avenues for wireless innovation. The 2013 Memorandum further stated that where technically and economically feasible, spectrum sharing can and should be used to enhance efficiency among all users and to expedite commercial access to additional spectrum bands, subject to adequate interference protection for Federal users, especially users with national security, law enforcement, and safety-of-life responsibilities.

1.1 NTIA Fast Track and 1755-1850 MHz Assessment Reports

In response to the 2010 Presidential Memorandum, NTIA undertook a “fast-track” review of several bands that could be reallocated to mobile use, including the 1675-1710 MHz band and the 1755-1780 MHz band, and proposed exploring Federal/non-Federal sharing of the 1755-1850 MHz band [5]. NTIA recommended that the 1695-1710 portion of the 1675-1710 MHz band be made available for non-Federal wireless broadband systems, subject to geographic sharing requirements based on “Exclusion Zones” around specified Federal meteorological earth station sites. NTIA deferred making recommendations concerning the 1755-1780 MHz band, however, because it could not complete its evaluation of the 1755-1780 MHz band by the October 2010 “fast track” deadline [4]. NTIA then invited Federal agencies with operations in the larger 1755-1850 MHz band to assess the feasibility of relocating from the 1755-1850 MHz band within ten years and to determine whether their respective systems could transition out of the 1755-1780 MHz band within five years, the conditions under which relocation could be accomplished, and the costs associated with the corresponding relocation.

Based on the assessments from these Federal agencies, NTIA concluded in March 2012, in the NTIA 1755-1850 MHz Assessment Report, that while it would be possible to repurpose all 95 megahertz of the 1755-1850 MHz band, several significant challenges would have to be met. These included the high cost and long timeline of repurposing 95 megahertz of spectrum, estimated at approximately \$18 billion over 10 years, assuming relocation of most existing Federal users, not including costs to relocate incumbent non-Federal users in the Federal agencies’ preferred destination bands. Considering the critical challenges related to the estimated timelines, costs, and complexities of completely clearing Federal users currently in the 1755-1850 MHz band, NTIA proposed a new path forward for consideration “that relies on a combination of relocating Federal users and sharing spectrum between Federal agencies and commercial users while ensuring no loss to critical capabilities.” Additionally, NTIA stated based on a review of the agency evaluations, that it is feasible to make the 1755-1780 MHz band available for commercial broadband wireless in five years—subject to exclusion zones and new allocations for Federal use of other spectrum bands, including 2025-2110 MHz and 5091-5250 MHz. NTIA did not evaluate the possibility for exclusive non-Federal use of the 1755-1780 MHz band in the NTIA 1755-1850 MHz Assessment Report.

1.2 2025-2110 MHz Spectrum

The National Aeronautics and Space Administration (NASA) operates earth stations in this band for tracking and command of manned and unmanned Earth-orbiting satellites and space vehicles either for Earth-to-space links for satellites in all types of orbits or through space-to-space links using the Tracking and Data Relay Satellite System (TDRSS). These earth stations control ninety domestic and international space missions including the Space Shuttle, the Hubble Space Telescope, and the International Space Station. The National Oceanic and Atmospheric Administration (NOAA) operates earth stations in this band to control the Geostationary Operational Environmental Satellite (GOES) and Polar Operational Environmental Satellite (POES) meteorological satellite systems. The data collected by the sensors on the GOES and POES systems are used by the National Weather Service (NWS) for short-term and long-term weather monitoring and forecasts. In addition, this is a shared frequency band that is used by non-Federal fixed and transportable ENG systems.

The FCC Proceedings and Rules (FCC-03-134A1, FCC-13-102-A1) suggested that the spectrum available for Federal Government operations will be displaced from the band 1710-1850 MHz as a result of making the 1710-1755 MHz segment available to support the introduction of new non-Federal Government Advanced Wireless Services (AWS), including third generation wireless

("3G") systems. These proposals were consistent with the U.S. Department of Commerce's 2002 Viability Assessment, the implementation of which would substantially clear the band 1710-1755 MHz of Federal Government operations that would have otherwise impeded the development of new nationwide AWS service. Specifically, it was proposed to allow the U.S. Department of Defense to use the band 2025-2110 MHz, on a co-equal, primary basis with non-Federal Government operations, for earth stations at 11 sites that support military space operations (also known as tracking, telemetry, and commanding or (TT&C)). Over time, DOD access to the band 2025-2110 MHz for TT&C Earth to space transmissions ("uplinks") may make more spectrum available in the band 1755-1850 MHz for absorbing certain DoD systems displaced from the band 1710-1755 MHz. In addition, it was proposed to permit the military services to operate stations in the 2025-2110 MHz band on a secondary basis at six sites in the southwestern region of the United States [1].

In October 2004, the FCC authorized the DoD for limited operation in the 2,025–2,110 MHz TV Broadcast Auxiliary Services band (FCC Office of Engineering & Technology Docket 00-258 Seventh Report & Order). The operation was constrained to 11 fixed sites, for Space Ground Link System uplinks, which were then in federal government spectrum in the L-Band, at 1,761–1,862 MHz, (the 11 sites were specified in Footnote US346 to the FCC Table of Allotments). These uplinks were required to protect all existing 2 GHz TV Broadcast Auxiliary Service (BAS) operations, including mobile (TV Pickup) ENG operations. To that end, on April 30, 2009, the Society of Broadcast Engineers and the DoD negotiated a formal Memorandum of Understanding that required protecting the noise floor of ENG receivers not just to the 1 dB noise threshold degradation criteria specified in Section 2.5.5 of EIA/TIA TSB-10F, but intentionally to an even more stringent 0.5 dB noise threshold degradation. This MoU was uploaded to the ET Docket 00-258 record on Dec. 29, 2009, by the Engineers for the Integrity of Broadcast Auxiliary Services Spectrum, to ensure its availability.

The March 31, 2014, GN Docket 13-185 R&O expanded the limited DoD co-primary status in the 2 GHz TV BAS band for just 11 specific sites and for Space Ground Link System (SGLS) uplinking only, to co-primary status without site restrictions and for a multitude of fixed and mobile uses by DoD. This included, for example, Small Unmanned Aerial Systems, Tactical Targeting Network Technology, Tactical Radio Relay and High-Resolution Video Systems.

1.3 Required Protections

However, the GN 13-185 R&O included a clear requirement that newcomer DoD operations protect all incumbent TV BAS operations. According to new footnote US92 to the FCC Table of Allotments:

"In the band 2025-2110 MHz, Federal use of the co-primary fixed and mobile services is restricted to military service and the following provisions apply:

(a) Federal use shall not cause harmful interference to, nor constrain the deployment and use of the band by the Television Broadcast Auxiliary Service, the Cable Television Relay Service, or the Local Television Transmission Service. To facilitate compatible operations, coordination is required in accordance with a Memorandum of Understanding between Federal and non-Federal fixed and mobile operations. Non-Federal licensees shall make all reasonable efforts to accommodate military mobile and fixed operations; however, the use of the band 2025-2110 MHz by the non-Federal fixed and mobile services has priority over military fixed and mobile operations.

(b) Military stations should, to the extent practicable, employ frequency agile technologies and techniques, including the ability to tune to other frequencies and the use of a modular retrofit capability, to facilitate frequency sharing of this band with incumbent Federal and non-Federal operations.”

1.4 The Status Quo: Traditional Spectrum Sharing Approach

Traditional DoD spectrum sharing practices are based on mitigating interference where a largely manual process of interference and spectrum management plays a crucial role in realizing “spectral” coexistence among operational, transitioning, and incumbent systems. Interference management involves conducting a thorough spectrum support risk assessment (SSRA) to determine interference implications of transitioning systems on the incumbent system; this is detailed in NTIA Report 05-432. An interference risk assessment is then conducted to ensure that each transitioning system complies with the applicable DoD and National spectrum management policies. In particular, transitioning systems must not cause harmful interference to incumbent systems. The risk assessment recommends interference protection criteria (IPC) [6] to foster spectral coexistence between transitioning and incumbent systems. In particular, the spectrum sharing policy recommends conservative interference contours (exclusion zones) to ensure minimal interference implications to incumbent systems. The interference contour is defined by a combination of channel spacing and distance separation metrics. Because it uses conservative propagation predictions, the interference-avoidance-based approach by its very nature poorly utilizes spectrum on a spatial basis. Moreover, the current spectrum sharing practice is procedurally cumbersome; by policy, a formal risk assessment must be performed for each pair of transitioning and incumbent systems. Furthermore, the current practice lacks the flexibility to accommodate new and advanced system capabilities.

The remainder of this document is organized as follows. In Sections 2 and 3, we cover background information on ENG and TDL systems, respectively. In Section 4, we review current state of the art techniques for spectrum sharing between civilian and military systems, and discuss pros and cons of existing solutions, as well as metrics for comparison and evaluation. In Section 5, we provide recommendations that combine best practices with new approaches to this sharing problem.

2. Understanding ENG Systems

“Electronics News Gathering” is a general broadcast news industry term referring to utilization of modern audio/video and communications technology for gathering and presenting news. News reports are gathered at their source and relayed via microwave links to television broadcast locations for edit and possible inclusion in complete newscasts. Microwave links in the 2025-2110 MHz band are of interest in this recommendation. It is noted, nevertheless, that other techniques are available and include satellite links, microwave links at different frequencies and “bonded cellular” which aggregates cellular radio channels to the degree required to carry the desired audio/video information. Remote sources of ENG information include small trucks (vans), helicopters and portable units all carrying microwave communications equipment. The ENG van or helicopter transmitter obtains data from audio / video collection devices (cameras, microphones, etc.), encodes the data, and then modulates and transmits this data to an ENG receiver system using one of a variety of communications modulation techniques. The transmit antenna of the ENG van is often highly directional and needs to be carefully positioned toward the ENG receive site to optimize the RF link.

The ENG receive system may be located in a remote location away from the news television station. The ENG communications system includes the capability for a Transmission Operator (TO) to remotely control both elevation and azimuth of a highly-directional receive antenna to point that antenna in the direction of the ENG source (van or helicopter). This pointing operation is often manual during which the TO slews the antenna direction while monitoring received power. In addition, the polarization of the receive antenna is remotely controllable between Right-Hand Circular Polarization (RHCP) and Left-Hand Circular Polarization (LHCP) to accommodate a transmit signal polarization change due to a required/requested building or mountain bounce, thus eliminating the Polarization Dependent Loss (PDL) associated with a polarization reversal. The transmit antenna of the ENG source (van or helicopter or other) is also directional and is manually pointed. Typical ENG scenarios are illustrated in Figure 1. The ENG receiver is often equipped with filters to aid in the elimination of out-of-band emissions.

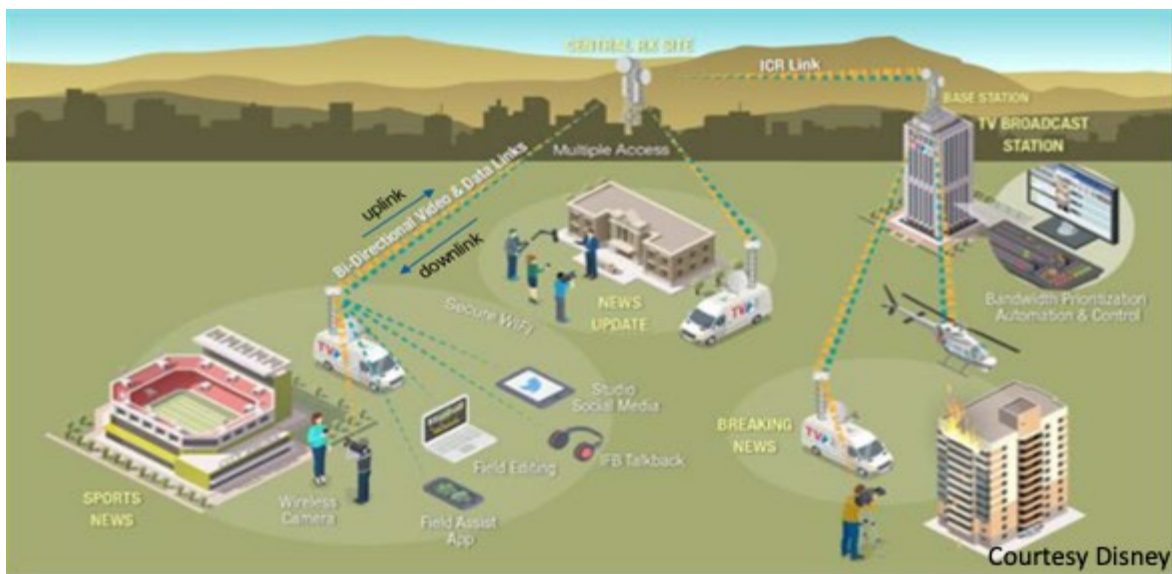


Figure 1: ENG Operation

In the U.S., ten Broadcast Auxiliary Service (BAS) channels are available for ENG microwave communications. In addition, two 500 kHz bands are reserved for Data Return Link (DRL) channels, which are provided for “handshaking” between receive and transmit sites; each DRL channel is 25 kHz wide, so there are 20 DRL channels on each side. However, the ENG community prefers to setup RF links via cellular communication, so the DRL links are not typically used. Channels one through seven including the DRL bands are located in the 2025-2110 MHz band as shown in Figure 2.

ENG communications systems typically use one of the following modulations: Digital Video Broadcasting-Terrestrial (DVB-T) (QPSK), DVB-T (16 QAM) [7] or others. It should be noted that the choice of modulation has evolved and may evolve further. The choice of modulation strongly affects the coexistence performance between the ENG communications and possible DoD spectrum sharing options. Transmission path characteristics between ENG transmitter and receiver is highly variable and may include obstructions, foliage, reflections and other physical characteristics affecting communications performance. The transmission path between the potentially interfering DoD asset and the ENG receiver experiences similar conditions. Path characteristics (including average path loss) strongly impact the spectrum sharing potential of the ENG system.

Broadcasters currently coordinate BAS channel use between local stations through local communities of interest using email, spreadsheets and norms developed through local ad-hoc agreements between users. Each news broadcaster typically utilizes more than one BAS channel. Each local BAS Channel coordinator executes the deconfliction responsibility in a manner that works for local users but results in significant variation in the ‘roll up’ of channel use data at the national level.

| | | | | | | | | | | | | | | | | | | | |
|-------------|------|---------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|---------|------|
| | 2025 | DRL 1 | 2025.5 | Channel 1 | 2037.5 | Channel 2 | 2049.5 | Channel 3 | 2061.5 | Channel 4 | 2073.5 | Channel 5 | 2085.5 | Channel 6 | 2097.5 | Channel 7 | 2109.5 | DRL 2 | 2110 |
| Width, MHz | | 0.5 | | 12 | | 12 | | 12 | | 12 | | 12 | | 12 | | 12 | | 0.5 | |
| Center, MHz | | 2025.25 | | 2031.5 | | 2043.5 | | 2055.5 | | 2067.5 | | 2079.5 | | 2091.5 | | 2103.5 | | 2109.75 | |

DRL - Data Return Link - Primarily used for helicopter TV pickup to steer antenna to receive site

Figure 2: ENG Channel Assignments

The ENG industry has assigned a National Coordinator to be the primary interface for BAS deconfliction with DoD. The relatively rudimentary systems support, variations in local collaboration and risk averse protection decisions contribute to periods of fallow BAS spectrum that could be more efficiently used. Near-real-time coordination workflow, better confidence between communities of interest through shared situational awareness and semi-automated system controls would reduce spectrum use opportunities lost through the current manual deconfliction mechanisms. Additional detail regarding ENG equipment characteristics and operational procedures is available via contact with the BAS/ENG national and local coordinators.

3. Understanding TDLs

The DoD uses a variety of wireless communications waveforms to exchange digital data for command, control, and communications. Tactical Data Links are often used to maintain a common situational picture among participants in an operational area using the link for data exchange. The communications often occur as computer-to-computer interactions. These links provide a secure method of communicating, often employing various methods of securing the data as well as maintaining the resilience of the waveform. There are a variety of frequency bands that are used for the communications, as links have been implemented at frequencies from the HF band well into the millimeter wave band. The number of participant nodes, data rate, latency, protocols, range and other characteristics are uniquely defined for each link.

The primary interest of the NSC Spectrum Superiority Working Group is with advanced tactical data links that operate from 1-3 GHz, as these are primarily impacted by the AWS-3 spectrum auction, the need for DoD to share a smaller spectrum band for testing and training, and the opportunity to share previously prohibited bands with commercial providers. These included, for example, Small Unmanned Aerial Systems, Tactical Targeting Network Technology, Tactical Radio Relay and High-Resolution Video Systems. While tactical data links in these bands would prefer to use the broadest collection of frequencies to achieve the best data rates and robustness, practical considerations significantly reduce the allocated operational band during an exercise. The trade-off of providing tactical data links with access to bands that are now available for sharing is balanced by the requirements to share those bands without impacting the commercial users. The methods that are being developed in this document by the MIL-CIV Task Group are intended to provide a blueprint of sharing methodologies that can be tailored to a variety of sharing situations throughout military, federal and commercial enterprises and will achieve the strategic goals of the United States.

4. Spectrum Sharing Techniques

This section discusses a number of spectrum sharing techniques that are currently in use. We also discuss their advantages and limitations in the context of the TDL-ENG spectrum sharing problem.

4.1 Exclusion Zones and Protection Zones

An Exclusion Zone (EZ) defines a geographical area in which potential RF interferers are not allowed to operate when the radio network of interest (the victim network) is operating. This area can be defined as a polygon rooted at the centroid position of the victim network. The resulting Protection Zone (PZ) is also a polygon that encompasses selected areas in which radios of the victim network can operate.

Exclusion Zones are typically computed pre-deployment where a computer simulates interference scenarios by varying radio parameters in time, space, and frequency. More specifically, the computer uses a Monte Carlo approach with thousands of iterations on EZ/PZ distance computation for one data point of a variable (e.g., receiver's azimuth of a radio equipped with a directional antenna), each time randomly varying other variables (e.g., radio geolocations, antenna heights, transmission times, etc.) to obtain a measure of confidence in the estimate (e.g., 95% confidence interval). Monte Carlo techniques have been used to derive EZ distances between military radars and cellular broadband radios – for example, in the 3.5 GHz NTIA study conducted by the NTIA in 2015 [1]. In each iteration, the goal is to find the minimum distance at which the Signal to Interference plus Noise Ratio (SINR) from an intended emitter reaches the minimum required value (defined a priori). The SINR is expressed as the reception power of the intended signal over the aggregate interference power plus estimated 'local' noise. The aggregate interference power is the sum of individual interference power levels, with each individual power level expressed as a function of the effective radiated power (transmit power and transmit gain), propagation loss as an exponential decaying function of distance, receiver antenna gain, frequency-dependent rejection, and other receiver internal losses (cable, insertion, etc.). Interference analysis between two networks, such as TDL and ENG, needs to be considered bidirectionally; that is, the EZ calculation needs to be derived for the benefit of each network and the maximum EZ distance, for both network perspectives, needs to be used for rule generation or other actions. PZ can be calculated using a similar approach with the intent, for example, not to cause interference to another network.

Another method of generating the Exclusion and Protection Zones is an online method in which EZ and PZ are computed on the fly to generate dynamic spectrum sharing rules. Typically, many of the radio parameters (e.g., location, center frequency, channel width, antenna pointing, antenna polarization, etc.) are fixed at the time of calculation. Small variations around the fixed parameters to capture possible future states are possible. The EZ & PZ derivations of the method described in the paragraph above apply here. In both methods of analysis, traditional calculations often use quasi-static noise floors with an underlying assumption of stable/healthy RF components (power amplifier, LNA, mixers, etc.). Improvements can be made to these calculations with a more accurate estimation of the rise in the in-band noise floor at the victim before it happens. Indeed, radio front-end components (on transmit and/or receive) might increasingly become defective, creating harmful interference during operations. During pre-deployment, one can use behavioral models of the RF components (time, frequency). During online operations, one can rely on historical raw behavior data (e.g., signal snapshots) obtained in near real time either by directly polling the radios themselves (if their Application Programming Interfaces (APIs) allow) or by relying on external sensors. Based on the data collected (e.g., power

spectral densities), one can estimate the interference power contribution to the victim noise floor, which contributes to the EZ distance derivation.

Generating exclusion zones is a rather common practice for spatial spectrum sharing. In the case of TDL-ENG, this could manifest in the form of protecting a small area required for a pencil beam from the transmitter and the ENG-receiver. However, this is true only if one has a priori knowledge of a lot of information regarding the ENG receiver including location, antenna height, polarization, pointing angle, terrain frequency band of operation etc. When this information is not known ahead of time, which is usually the case, these exclusion zones tend to be rather large. This is especially true if the receiving ENG antenna is on top of a building or worse, a mountain. Case in point is the ENG receiving antenna located on top of Mount Wilson above Los Angeles, at an elevation of roughly 5,500 feet. Line of sight distance to an aircraft flying at 35,000 feet would be over 350 miles. Exclusion zone also assumes a priori knowledge of where the receiver is pointed. While this is fine if the receiver is pointed in a fixed direction the exclusion zone would expand drastically if the exact direction is not known. Compounding this, exclusion zone may or may not be active 100% of the time. Once again, you would have to have a priori knowledge of whether the receiver you are interfering with is active at any given point in time. Without this knowledge, there is a risk that the exclusion zone would have to be enforced 100% of the time.

4.2 Spectrum Access Systems and Databases

A Spectrum Access System (SAS) is a software service that leverages RF Situational Awareness (RFSA) and various calculation services to manage spectrum access for a collection of networked radio systems (e.g., a tactical radio system) according to spectrum sharing policies. RFSA can be synthesized from a variety of sources including dedicated sensors (e.g., the Citizens Broadband Radio Service (CBRS) Environmental Sensing Capability (ESC)), online and third-party databases, managed radio information (e.g., locations, operational parameters, performance, sensing data, ESC), unmanaged but cooperating radio systems (e.g., informing incumbents), other spectrum management and spectrum access systems, and other relevant APIs and data feeds. RFSA state information is normally stored in a database and augmented by calculation services that estimate RF environmental conditions (e.g., interference and performance). For inquiries about spectrum availability, for reporting local information and for receiving spectrum assignments, radios can communicate with the SAS directly or via a proxy (e.g., a CBSD proxy or a network manager such as ATOM or Black Sails). The spectrum sharing policies that are generated by the SAS describe the rules by which spectrum can be (and / or should be) used by secondary systems reflecting regulatory requirements and mission objectives.

Coordination of Spectrum Resource Users

For a given size and granularity of dimensioned spectrum resource unit, access and usage can be governed/coordinated or scheduled by a scheduler-controller deciding via a dynamic reasoning function and executing control/scheduling actions based upon knowledge of the users (emitters) and their allocated and/or actual EM energy emissions. This knowledge may be from a pre-populated database that contains this information or sensed information or a hybrid of both. This sensing may include spectrum sensing or detection of emitter beaconing (in-band or any out of band beaconing/signaling).

The resource allocation schedule that is to be followed may be determined either ahead of time or on the fly. In either case the allocations themselves may be changed dynamically, at some time granularity, as in the case of a Dynamic Spectrum Coordination System. The Users include those which are named/authorized, and those which are generally authorized. Though

unwelcome, unauthorized emitters are also a type of spectrum user that is addressed by the system. The Spectrum usage of these users can be for any purpose: communications, sensing, radar, etc. and sharing can be within or between any combination of users and usages and any subtypes of these; for example Long-Term Evolution (LTE) / 3GPP-family of Radio Access Technologies (RATs) including unlicensed and hybrid-licensed, as well as increasingly Open RAN-informed systems.

A dynamic spectrum coordination system may schedule based on any prioritization of these users and usages. A dynamic spectrum coordination system can roughly be considered either a macro-controller or micro controller depending on the granularity of the units in the 3D and 4D Spectrum Resource Envelopes.

US 3.4 GHz CBRS SAS Example

The US 3.5GHz CBRS Spectrum Access System is an example of a type of Dynamic Spectrum Coordination System which pioneered large-scale dynamic/temporally-shared 3-tier (Incumbent, Priority Access Licensed, and Generally Authorized Access Users) spectrum sharing at a notably smaller geographic granularity. It is well-suited to the specific needs of the US 3.5GHz band and provides a valuable example for subsequent dynamic spectrum coordination systems that can be more generalized and evolved to meet the needs of other spectrum bands. Currently, there is work underway to incorporate a directional component to the current spatial sharing approach in the CBRS Spectrum Access System via 2D and 3D beam-based extensions.

European LSA / Dynamic LSA Example

In response to the European Commission 2014 recommended harmonized technical conditions for sharing in the 2.3GHz band, the European Conference of Postal and Telecommunications Administrations (CEPT) generated responsive technical recommendations. For this and other potential bands, many associated National Regulatory Authorities including France, Portugal, Finland and others have considered, explored, or trialed Licensed Shared Access (LSA) schemes, and evolutions to LSA such as time-varying Dynamic LSA and 3-Tier LSA. The initial LSA approach provided only for exclusive shared use of the spectrum in location and frequency with the incumbent who uses its spectrum allocation infrequently or less extensively.

Japanese Local 5G Example

In its Radio Act of 2020, the Japanese Ministry of Internal Affairs and Communications (MIC) implemented a pioneering spectrum sharing approach in the 4.6-4.9 GHz, 28.2-28.3 GHz and 28.3-29.1 GHz bands to allow multiple coexisting Private Local 5G implementations in small geographically limited coverage areas such as a factories, campuses, and municipalities. In its 2020 Frequency Reorganization Action Plan, MIC has under various stages of study further geographic and dynamic spectrum sharing of the following bands: 1.2 GHz, 2.3 GHz, 2.6 GHz, 5.8 GHz, 5.9 GHz, 9 GHz, 26 GHz, 28 GHz, 38GHz, 40 GHz.

4.3 Spectrum Sensing for Dynamic Spectrum Access

Dynamic Spectrum Access technologies bring paradigm shift to shared spectrum use by enabling opportunistic access to under-utilized spectrum, primarily allocated to incumbent systems (ENG System). Spectrum sensing is a key enabler of DSA [8-9], where it provides the ability to characterize spectral activity to determine opportunistic access to frequency band of interest. To enable DSA approach for shared spectrum use, a spectrum sensing technique is used to determine if ENG system is transmitting or not and what channel ENG is operating on. If TDL location is close enough to cause interference (combined antenna gains and propagation loss), then DSA-enabled TDL abandons the channel to avoid interference needed.

In general, the DSA sensing rule depends on the spectrum access scheme employed by the legacy system (ENG in this case), which also determines the associated challenges. The traditional approach for opportunistic spectrum access requires the DSA system to sense the primary signal of interest. However, this is not as easy as it seems and is elaborated further below in the context of three types of Legacy Systems that may affect how DSA sensing is conducted.

Legacy System Type 1

A Time Division Duplex (TDD) system is an example of Legacy System Type 1. These are either full duplex systems with simultaneous two-way communications or half duplex, but basically share the same channel for uplink and downlink, as shown in Figure 3. Example of Legacy Systems Type 1 include: Joint Tactical Radio System (JTRS) Wideband Networking Waveform (WNW), JTRS Soldier Radio Waveform (SRW), Tactical Radio Relay (TRR), High-Capacity Line-of-Sight (HCLOS), and Air Combat Training Systems (ACTS).

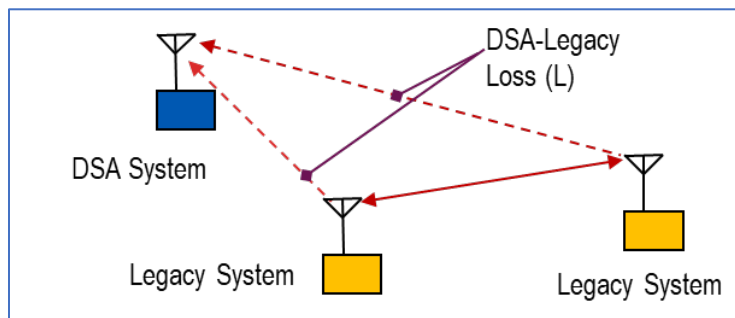


Figure 3: Example Legacy Systems Type 1: JTRS WNW, JTRS SRW, Tactical Radio Relay HCLOS, ACTS.

Legacy System Type 2

A Frequency Division Duplex (FDD) system is an example of Legacy System Type 2. These systems use two separate communications channels; each node transmits on one channel and receives on another channel as shown in Figure 4. Example of Legacy Systems Type 2 include LTE, most point-to-point microwave links, and satellite operations.

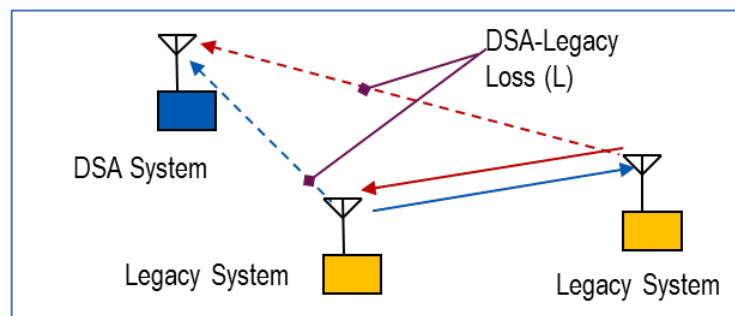


Figure 4: Example Legacy Systems Type 2: LTE, most point-to-point microwave links, satellite operations.

Legacy System Type 3

A Silent Receiver/Hidden Nodes is an example of Legacy System Type 3. As shown in Figure 5 below, in these types of systems, the receiver does not transmit at all. Figure 5 shows examples of Legacy Systems Type 3 include ENG, aeronautical mobile telemetry, television, wireless

microphones, most High Resolution Video (HRV) systems, most SUAS data links, DoD video surveillance / robotics.

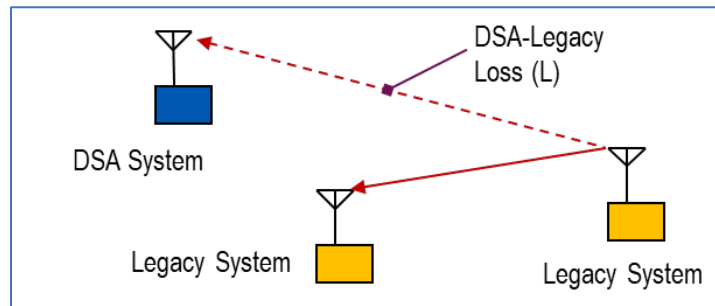


Figure 5: Example Legacy Systems Type 3: ENG, aeronautical mobile telemetry, television, wireless microphones, most HRV systems, most SUAS data links, DoD video surveillance/robotics.

The hidden node problem is exacerbated if the transmitting end of the link utilizes directional antenna, especially when the DSA system is in the main beam of the receiver (causes interference) while simultaneously being in the back lobe of the transmitter (cannot detect transmitter). Not being in the main beam of the transmitter the signal would be too weak for DSA to detect. The only time that sensing of the legacy signal itself will work is when the DSA TDL system is located either between the transmitter and receiver or behind the receive antenna. In this case, the area of protection will be very small since the link is likely short, in the range of a few tens of kilometers, in the second case, the DSA TDL system is less likely to cause interference since it is located behind the legacy antenna. With ENG links, this problem is amplified due to the short nature of the link, which generally does not exceed a few tens of kilometers. It is therefore unlikely that a fast-moving airborne intruder would find itself between the transmitter and the receiver.

For other DSA systems, this approach may provide poor performance (high interference to legacy user) due to the hidden node problem. Additionally, this approach does not account for TDL TX power, TDL antenna pattern, TDL-ENG RX propagation loss, nor the ENG RX antenna pattern (Figure 6).

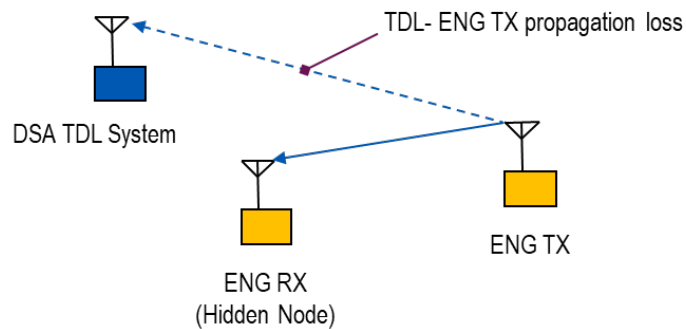


Figure 6: DSA Approach 1 senses the ENG signal.

4.4 Spectrum Sharing Performance Metrics

Spectrum sharing policy applicable to the 2025-2110 MHz band requires among other things: 1) zero harmful interference created to the incumbent ENG system by the transitioning DoD system; 2) zero modification to the incumbent ENG operating procedures. “Harmful interference” has been

defined to be an interference level of greater than -108 dBm within the receive bandwidth of the ENG receiver when the ENG system is operational.

Transitioning system interference at the incumbent receiver is a function of the operating parameters of both the incumbent and transitioning system, the antenna gains in the directions of interest, and the pathloss between the transmitters and receivers of interest. Pathloss is, of course, a strong function of distance and terrain and details of obstructions and reflectors on that terrain. For spectrum sharing performance estimation, pathloss estimation tools are used. Common pathloss estimation tools include 1) free space models [10]; 2) Okumura-Hata pathloss models [11-12]; 3) the government's Terrain Integrated Rough Earth Model (TIREM) [13]; 4) the ITU-R P.528 aeronautical mobile pathloss model [14]; and many other models. Other propagation phenomenon also affect spectrum sharing. Some of these phenomena include shadowing losses and multipath.

It is desirable, but not essential, that the spectrum sharing system be independent of pathloss model although pathloss models are required to estimate system performance. If the DSA algorithm is independent of pathloss model, that DSA algorithm does not estimate propagation details for use in its reasoner. Instead, the DSA algorithm makes decisions based on actual experienced pathloss. In this case, pathloss model accuracy affects system performance prediction and not actual system performance. Some sharing systems (e.g., database systems) nevertheless depend on estimated pathloss for the calculation of exclusion zones and these systems may be considered herein. It is conjectured that DSA sharing performance comparisons are only weakly dependent upon the selected pathloss model. Actual performance is, of course, critically dependent upon actual pathloss.

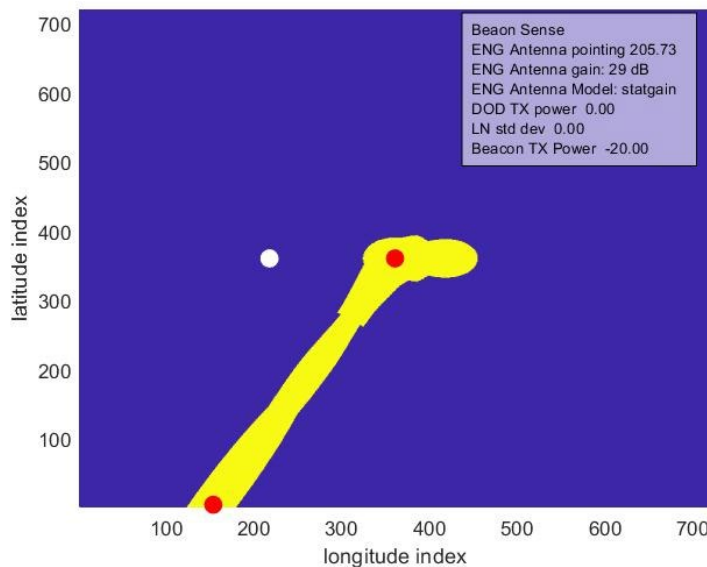


Figure 7: Calculated Exclusion Zone (yellow) for a specified AOI.

Comparison of spectrum sharing concepts is based in part upon the estimated geographic extent of exclusion zones. An area of interest (AOI) is defined, and a system model is created taking into account the terrain, the locations of the incumbent and transitioning systems, DSA system parameters and other system details. Link calculations are performed to calculate whether harmful interference occurs at the ENG incumbent receiver. If there is harmful interference, the

particular transitioning system transmitter location is declared within the exclusion zone for the system parameters being considered. This calculation is repeated for each transitioning system transmit location as that location is raster scanned over the entire AOI. Thus, a graphic illustrating the exclusion zone is created for the DSA system.

Figure 7 illustrates the results of the exclusion zone estimation for an example system. Calculated Exclusion Zone (yellow) for a specified AOI. Red dots are ENG system transmitter and receiver. White dot is transitioning system receiver. Transitioning system transmitter has been raster scanned over all locations (both blue or yellow points) in the AOI. High gain antennas are presumed for every transmitter and receiver. The STATGAIN antenna model [15] is used throughout. It should be noted that the yellow exclusion zone is the area where the ENG receiver antenna has its maximum gain.

Using the modeling technique just described, DSA systems may be qualitatively compared. Quantitative comparisons are done by calculating the extent of the yellow and blue areas. The results of Figure 7 were calculated using the Hata pathloss model without shadow loss. This graphic may also be created using the TIREM pathloss model and including shadow loss. The performance metric must also include a time dependent component. That is, the DSA system must react rapidly to changes in spectrum use by the incumbent ENG system. Appropriate extensions to include a time component are being considered.

5. Recommended Practices for Co-existence Between TDLs and ENG

Traditional dynamic spectrum access (DSA) approaches, such as sensing and coordinated database approaches described in Section 4 each have their advantages and disadvantages depending on the types and characteristics of the TDLs and RF environments under consideration. For example, a coordinated database works very well under mostly stationary conditions (with TDLs either stationary or slowly mobile). Apriori knowledge of the geographic locations of all RF emitters, antenna heights, antenna pointing angles, antenna polarization, terrain, and frequency allocations is required for efficient operation. However, in situations involving fast-moving TDLs (e.g., aircrafts) and/or dynamic RF environment, maintaining a sufficiently accurate database may be difficult due to the highly dynamic environment and delays in propagating accurate information through the database. In an ideal world, all co-existing networks would update the database to create a feature-rich, accurate, and timely characterization of the environment. However, given the operational security (OPSEC) considerations for TDL systems – i.e., we don't want TDL locations or flight paths revealed in all cases – these database approaches by themselves will not be enough.

On the other hand, even though sensing can be an important tool in determining interference, sensing only approach can be unreliable due to hidden node issues and vulnerabilities to spoofing and denial of service attacks. Sensing of harmful interference at the ENG receiver itself may partially mitigate some of these problems. In the rest of this section, we discuss various practical sharing approaches that are amenable for the TDL-ENG spectrum sharing problem. Depending on the sharing use case of interest, one or a combination of these approaches may be optimal. It is recommended that system designs and constraints be carefully considered and their impact on performance metrics be evaluated for each use case of interest.

5.1 Approach 1: Beaconing and Sensing through DRL

In this approach, the ENG receiver transmits a DRL signal for the duration of time that the ENG signal is active, through the help of a beacon that is co-located with the ENG receiver. The TDL DSA system senses the DRL signal and, thus, directly estimates the DoD-to-ENG receiver isolation (i.e., combined propagation loss, antenna gain, and antenna directivity). The moving TDL system measures the beacon signal amplitude to effectively make an instantaneous path-loss measurement (based on a known, standard beacon signal transmit power) to determine the degree of exclusion distance and/or isolation needed to minimize interference to the ENG receiver(s) while closing the TDL link. This approach provides good performance since it does accounts for all relevant factors including: TDL TX power, TDL antenna pattern, TDL-ENG RX propagation loss, ENG RX antenna pattern, interference protection criteria, and the hidden node problem.

Figure 8 illustrates the basic principle of operation in the ENG situation. Sensing the DRL beacon is the main mechanism for the protection of the ENG receiver. Without the DRL signal, a sensing-based spectrum sharing system could detect the uplink ENG signal, but this does not directly estimate the DoD-to-ENG receiver link loss (propagation loss and antenna gain), resulting in the hidden node problem. The ENG receiver may be hidden from the DoD system; hence, the DoD system may cause interference. The DRL beacon uses the same dish as the ENG receiver, therefore, sensing the DRL signal by the TDL system solves the hidden node problem referenced in the previous section.

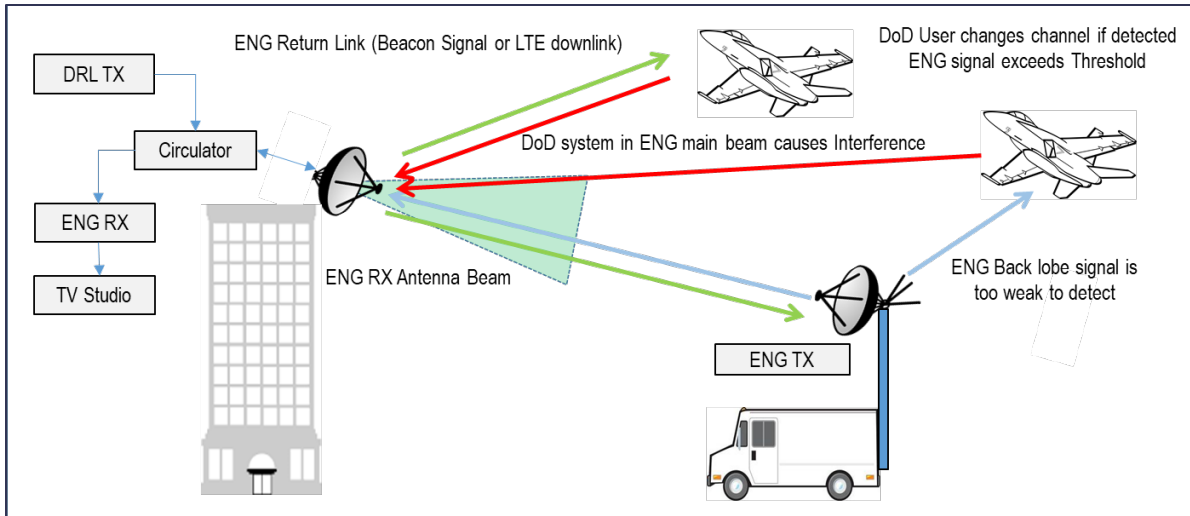


Figure 8: DRL-based sensing and beaoning.

DRL System Specifics

DRL is an approved band within the ENG channel plan. There is no regulatory approval needed to implement the DRL sensing approach. There are total of seven ENG channels spanning from 2025.5 MHz to 2109.5 MHz. On each side of those, there is a 500 kHz band, which has 20 DRL channels, each 25 kHz wide. The seven ENG channels overlap with six TDL channels as seen in Figure 9 below.

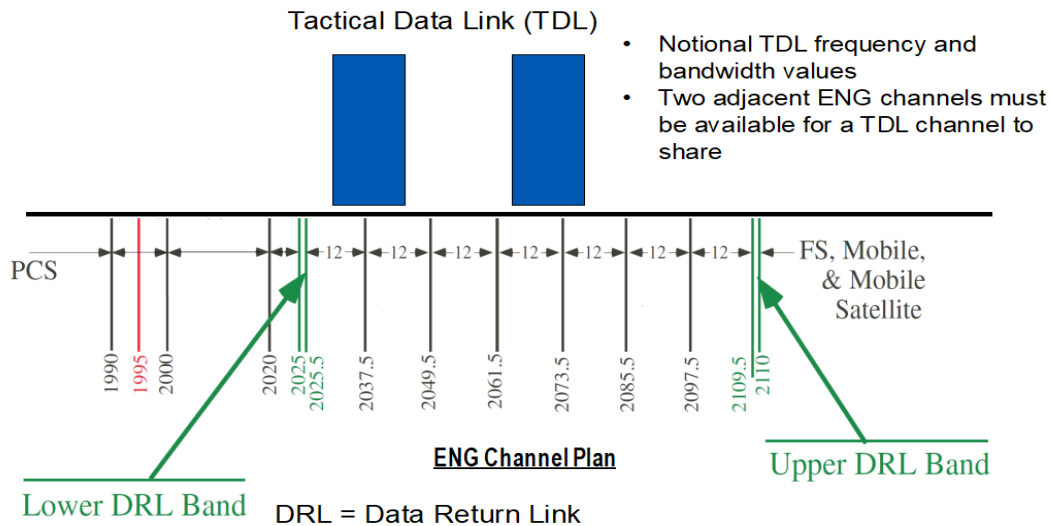


Figure 9: TDL and ENG spectrum channel plan.

In the DRL standard, the DRL frequency is not related to the ENG channel being used. The DRL frequency assignments are coordinated manually. Ideally, ENG transmitters pointing to ENG receivers at a common location are assigned maximally separated ENG channels. Similarly, DRL frequencies would be assigned to minimize interference to ENG receivers as well as interference from ENG transmitters. As part of this approach, we propose to use a nationwide standard of DRL frequencies that is related to the ENG channel being used.

DRL Beacon Frequency Plan

In the proposed DRL beacon spectrum sharing approach, if a DRL beacon signal is detected which corresponds to a certain ENG channel, then the overlapping TDL channels have to be vacated to prevent interference. DSA periodically detects on all DRL channels listed in Table 1. In this solution approach the corresponding DRL channels are chosen in such a way that they are as far separated from the ENG channels so as to avoid adjacent channel interference. However, it is up to the user and the use case to decide the mapping between the ENG and the DRL channel.

Table 1: The DRL Channel Plan Indicates the Occupied ENG Channel.

| ENG Channel | ENG Channel Center Frequency (MHz) | DRL Channel | DRL Channel Center Frequency (MHz) | DRL Band |
|--------------------|-------------------------------------------|--------------------|-------------------------------------------|-----------------|
| 1 | 2,031.50 | 23 | 2109.5625 | Upper |
| 2 | 2,043.50 | 25 | 2109.6125 | Upper |
| 3 | 2,055.50 | 28 | 2109.6875 | Upper |
| 4 | 2,067.50 | 3 | 2025.0625 | Lower |
| 5 | 2,079.50 | 5 | 2025.1125 | Lower |
| 6 | 2,091.50 | 8 | 2025.1875 | Lower |
| 7 | 2,103.50 | 11 | 2025.2625 | Lower |

DRL Transmit Power Level Determination

The DRL transmit power value is determined based on the DoD radio (TDL) transmit power and the maximum allowed ENG receiver interference level. For example, if the maximum allowed interference power within the 8 MHz bandwidth ENG channel was -108 dBm, and the TDL transmit power was 50 dBm, then the minimum TDL (at 13.3 MHz bandwidth) to ENG link loss (including the antennas) to avoid interference is 155.8 dB. If the DSA TDL detector system had a 6 dB Noise Figure (NF), then the noise level within a 25 kHz would be -124 dBm.

As the DRL transmit power is reduced, the DRL signal will be too difficult to detect using conventional fast Fourier transform (FFT)-based detection approaches. A DRL sub-noise feature detector will need to be used or the DRL signal bandwidth will need to be reduced. Assuming that -10 dB SNR sub-noise detection signal processing is used, then the minimum DRL signal amplitude that can be detected is -134 dBm. For the DRL transmitter to be detected at a 155.8 dB link loss, the DRL transmit power level needs to be 21.8 dBm. The same DRL signal can be used for all DoD systems in the 2025 MHz to 2110 MHz band (TDL, TRR, SUAS, and HRV).

The selection of the DRL transmit power is complex and has competing factors. A higher DRL transmit power provides additional interference margin (an advantage to the ENG users), and is easier to detect (reduced DSA system processing resources required); however, it is also more costly to implement in the DRL system (requires more filtering to avoid jamming the ENG receiver). However, in the interest of reducing beacon costs and spectrum impact, a lower power transmitter is desirable. Based on the analysis above, a DRL transmit power of around 20 dBm is considered to be the best choice in order to provide the necessary interference margin for most DoD systems, however, the optimal choice may vary based on the specific use case.

More information related to the DRL standard and its relevance to the current discussion is provided in Section 7.2.

5.2 Approach 2: Centralized Database and Distributed Sensing

A hybrid approach combines the hybrid use of exclusive and non-exclusive spectrum authorizations as well as the use of centralized spectrum coordination and distributed sensing spectrum coordination.

It is recommended that there should be hybrid primary and non-primary use of the ENG band. The current exclusive ENG band users would become primary user and others, such as DoD TDLs, Federal and civilian users could become non-primary users. This can be a two-tier or three-tier hybrid system. A two-tier system would have primary and secondary users with all secondary users at the same level. A three-tier system could split the secondary users into priority users and tertiary users. This is similar to the CBRS approach with CBRS Incumbent Access users, CBRS Priority Access users, and CBRS General Authorized Access users to fill the three tiers.

There are several dimensions to the spectrum sharing framework as shown in the following Table 2 with examples from [20]. As discussed in Section 4.3, a sensing only approach can be unreliable due to hidden node issues and may be vulnerable to spoofing and denial of service attacks. This is further complicated through the use of one-way as well as two-way ENG links and directional as well as omni-directional antennas used with ENG systems [21]. However, sensing can be important in determining interference and verifying compliance with sharing policies. For example, a sensor system such as the Environment Sensing Capability (ESC) that is part of the CBRS sharing solution could sense its environment to determine if it is being interfered with and report that interference. Here again there are significant challenges, as the ESC sensors may not be co-located with the ENG systems or may not have enough density to perform signal localization, in which case, the interference measured by the ESC system needs to be carefully translated to the perceived interference at the ENG receiver, thereby resulting in increased uncertainty.

Table 2: Comparison of Centralized and Decentralized Spectrum Sharing Frameworks

| Spectrum Sharing System Framework | Centralized | Decentralized |
|-----------------------------------|---------------------------------------------------|-------------------------------------------------------------|
| Coordinating | TVWS, Automated Frequency Coordination (AFC), SAS | Some Cooperative Intelligent Radio Network (CIRN) systems |
| Sensing | ESC | Listen-before-Talk (LBT), Dynamic Frequency Selection (DFS) |
| Informing | IIC | IIC, Beaconing |

A coordinated database approach can enable multiple disparate systems to share the spectrum and provide some assurance via ESC that the non-incumbent systems can be requested to stop transmitting in an exclusion area if the ESC systems are sensing interference. Or if there are no known non-incumbent systems transmitting in an area, then these users can defend that they are not the cause of interference. Another benefit of databases is the reduced amount of control traffic needed from a network perspective. However, a coordinated database only approach can be problematic due to spectrum inefficiencies (by requiring larger exclusion zones than necessary to afford the desired protection) and data curation inaccuracy issues. By the time a new spectrum update occurs in the database, the TDL antennas may have already moved to a new location and/or direction resulting in erroneous path-loss estimates and ill-suited spectrum policies.

Intermediate situations with TDLs in helicopters or drones (subject to terrain blockage at lower altitudes) may require a database with pre-loaded path-loss models that are gradually updated with “live” sensing information, which could be cumbersome.

A hybrid combination of the centralized and distributed approaches provides the greatest flexibility of operation. Spectrum sharing of the ENG band with other systems could have an informing approach where the ESC systems inform about their sensor measurements – either through informing a centralized coordinating function and/or also supporting beaconing for decentralized operation. The secondary systems would also coordinate amongst themselves through informing for centralized control and/or through beaconing. Beaconing also supports operation of systems that only have intermittent connectivity with the centralized coordinating system. Beaconing also supports coordination of a large number of independently operating devices as compared to a network of cooperating devices, such as a TDL network, which could potentially connect to a centralized coordinating system [22].

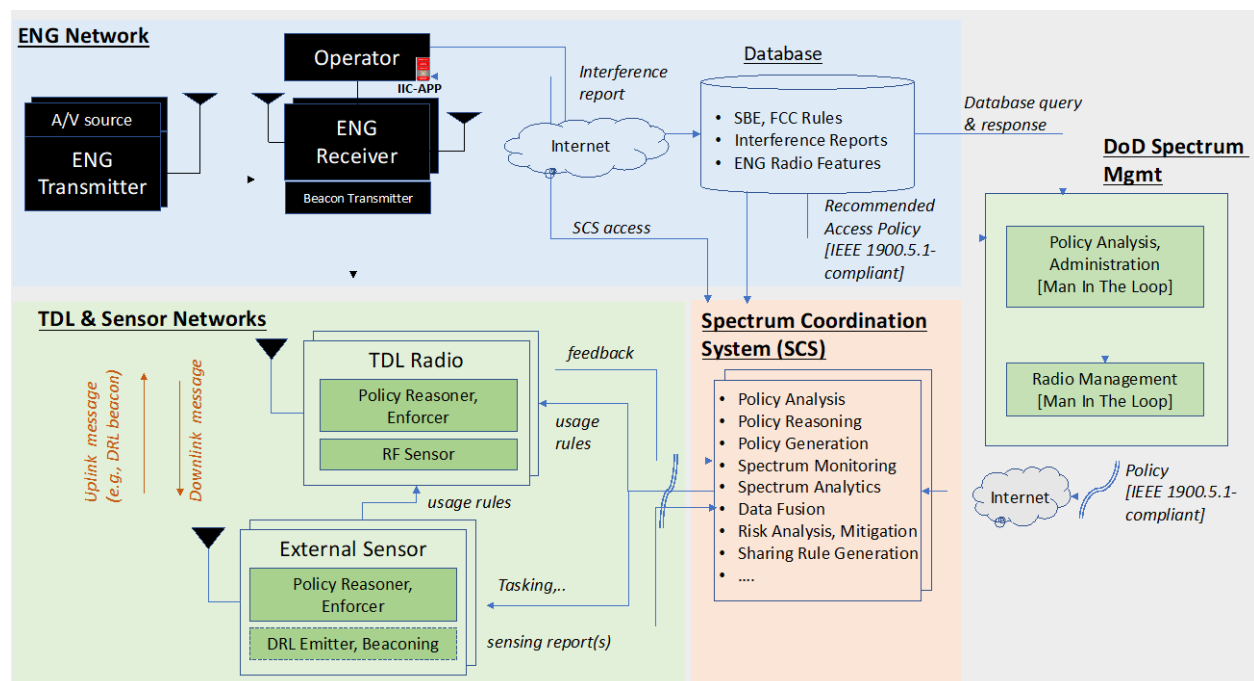


Figure 10: Recommended architecture for TDL-ENG coexistence.

As part of this recommendation, the following roadmap could be implemented going from today’s spectrum usage and systems to the proposed spectrum sharing solution. The proposed solution could become more inclusive over time:

Phase 1 – A centralized database approach with coarse exclusion zones.

Phase 2 – Add ENG and non-ENG system informing to the centralized database to provide better spectrum reuse – with potential interference that could be caused by mobile systems with directional antennas including sidelobes.

Phase 3 – Include sensing and beaconing to improve the spatial reuse despite mobility of the ENG and non-ENG systems.

To cover air-ground and ground-ground cases automatically and efficiently, a representative DSA architecture that combines both sensing and databases is presented in Figure 10. Recently proposed approaches for spectrum sharing in commercial networks leverage the near real time RAN Intelligent Controller (RIC) proposed by the O-RAN Alliance to execute closed-loop control algorithms that enable coexistence on the same spectral band between commercial cellular systems (LTE, 5G) and unlicensed users of the spectrum (e.g., WiFi) [23]. Signal detections algorithms including AI/ML algorithms can detect the presence of WiFi on a cellular channel and reconfigure the operational frequency while maintaining ongoing sessions with mobile users that are active through handover commands. While O-RAN currently assumes a centralized control architecture, it is conceivable that extensions enabling hybrid distributed / centralized control will be developed in the near future, which may be applied to the ENG-TDL coexistence problem.

5.3 Approach 3: Direct Measure of Interference at the ENG Receiver

This DSA approach is based upon the direct measurement of the transitioning system interference level at the incumbent ENG system receiver. If the interference level exceeds a predetermined coexistence threshold, system control processes are executed to adjust system parameters (reduce power, adjust antenna pointing, adjust polarization, change frequency, etc.). Figure 11 illustrates an example AOI with incumbent ENG system and transitioning DoD system.

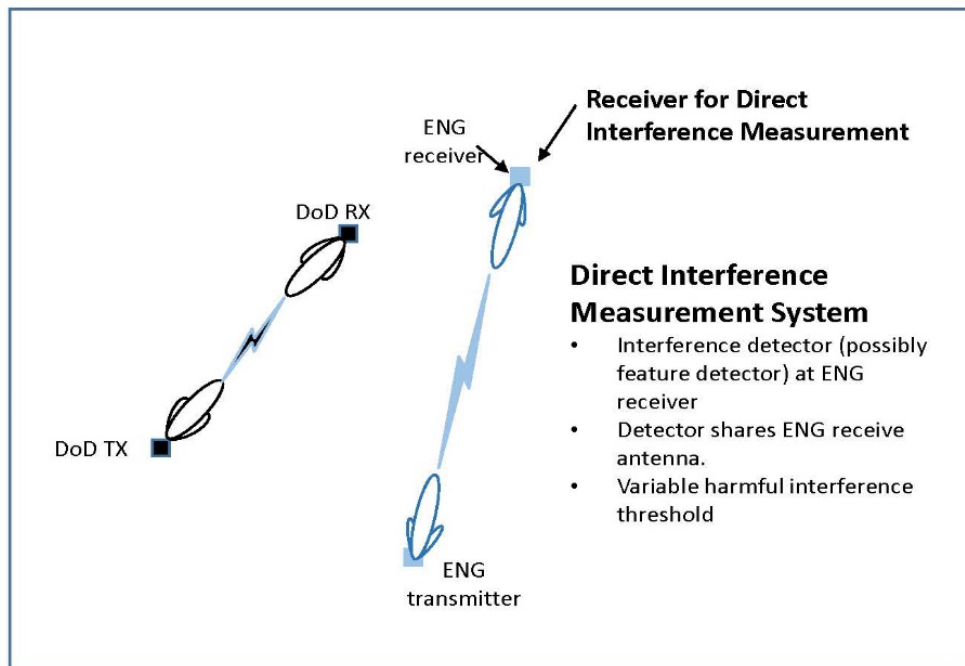


Figure 11: Area of Interest with incumbent ENG system and transitioning DoD system.

The interference measurement at the ENG receiver is done using a detector that may be implemented using a software defined radio (SDR). The implemented detector may use classical radiometer concepts or may use feature detector concepts. Both detection concepts have been thoroughly analyzed in the public literature (see [24] for radiometric detection and [25] for feature detectors). The SDR detector is attached to the IF port of an ENG receiver and thus the analyzed signal has followed an RF/IF path that is identical to the desired ENG waveform. No calibration to relate measured signal level to received SINR is required. The exact (notwithstanding accuracy

of the measurement itself) excess interference level is known and is used by the DSA system reasoner. The reasoner suggests adjustments to transitioning system transmit power and/or other system parameters. The reasoner input parameters are obtained via policies established during the design of this DSA system or may be data collected during operations. The minimum adjustment possible to mitigate harmful interference is recommended by the reasoner. That is, adjustments are not necessarily binary off/on adjustments. A human operator may be included in the DSA control loop or the procedure may be fully automated. The ability for non-binary DSA power adjustment allows the exclusion region boundaries to be soft. Soft boundaries potentially increase DSA sharing efficiency.

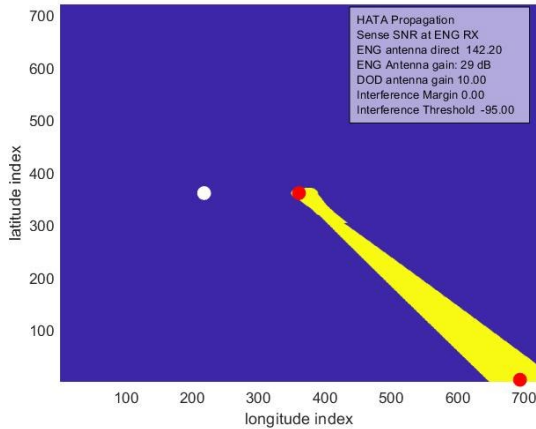


Figure 12: Calculated Exclusion Zone for Example System Using -95 dBm Interference Threshold. Shadowing Std Dev is 0 dB.

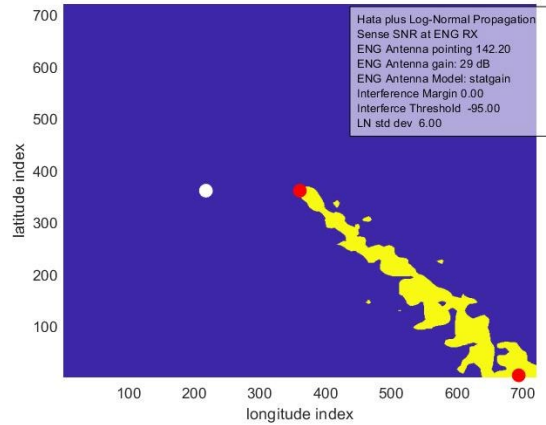


Figure 13: Calculated Exclusion Zone for Example System Using -95 dBm Interference Threshold. Shadowing Std Dev is 6 dB.

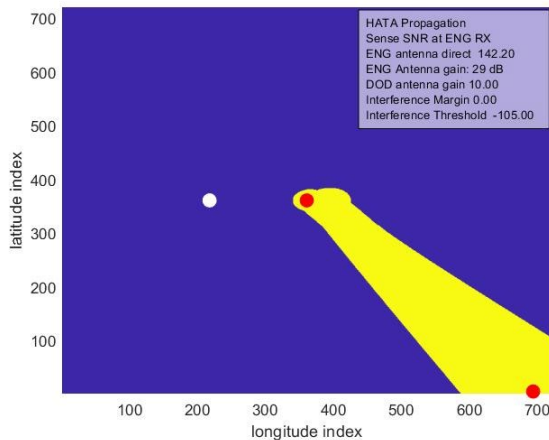


Figure 14: Calculated Exclusion Zone for Example System Using -105 dBm Interference Threshold. Shadowing Std Dev is 0 dB.

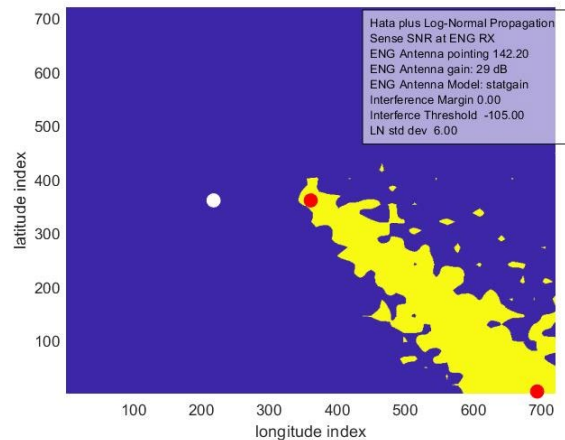


Figure 15: Calculated Exclusion Zone for Example System Using -105 dBm Interference Threshold. Shadowing Std Dev is 6 dB.

One metric for comparing the performance of the various sharing strategies is the achieved fraction of an area of interest where sharing is possible. Calculation of this metric for Approach 3 is done by assuming a fixed instance of all pathloss conditions and calculating (straightforward link budget calculations) the set of locations where sharing is possible. Note that similar calculations are done for the calculation of exclusion zones for database approaches to sharing.

The achieved area under Approach 3 is different from the exclusion zone calculation used in other DSA calculations. The calculation here assumes a fixed instance of all propagation conditions. These actual propagation conditions are accounted for in the interference measurement and therefore accounted for in the calculation of the performance metric. For other DSA systems, a margin of statistical uncertainty must be included in the exclusion zone calculations thus reducing the achievable area where sharing is possible. Figure 12 and Figure 13 illustrate the exclusion zones for an interference threshold of -95 dBm. Figure 12 uses 0 dB log-normal shadowing standard deviation and Figure 13 uses 6 dB log-normal shadowing standard deviation. Figure 14 and Figure 15 are similar except that the interference threshold is -105 dBm.

For Figure 12-Figure 15, the ENG receiver is located at the red dot in the center of the AOI. The ENG transmitter is at the lower right corner of the AOI. The DoD receiver is at the white dot to the left of the ENG receiver. The DoD transmit power is always adjusted to be the minimum possible to close the DoD link. The ENG receiver antenna uses a gain of 29 dB. The ENG receive antenna points directly at its partner transmitter. Observe that the exclusion i.e., the points where sharing is not possible (yellow coloring), is in the direction of the ENG receiver beam antenna and that the exclusion zone becomes larger as the interference threshold decreases.

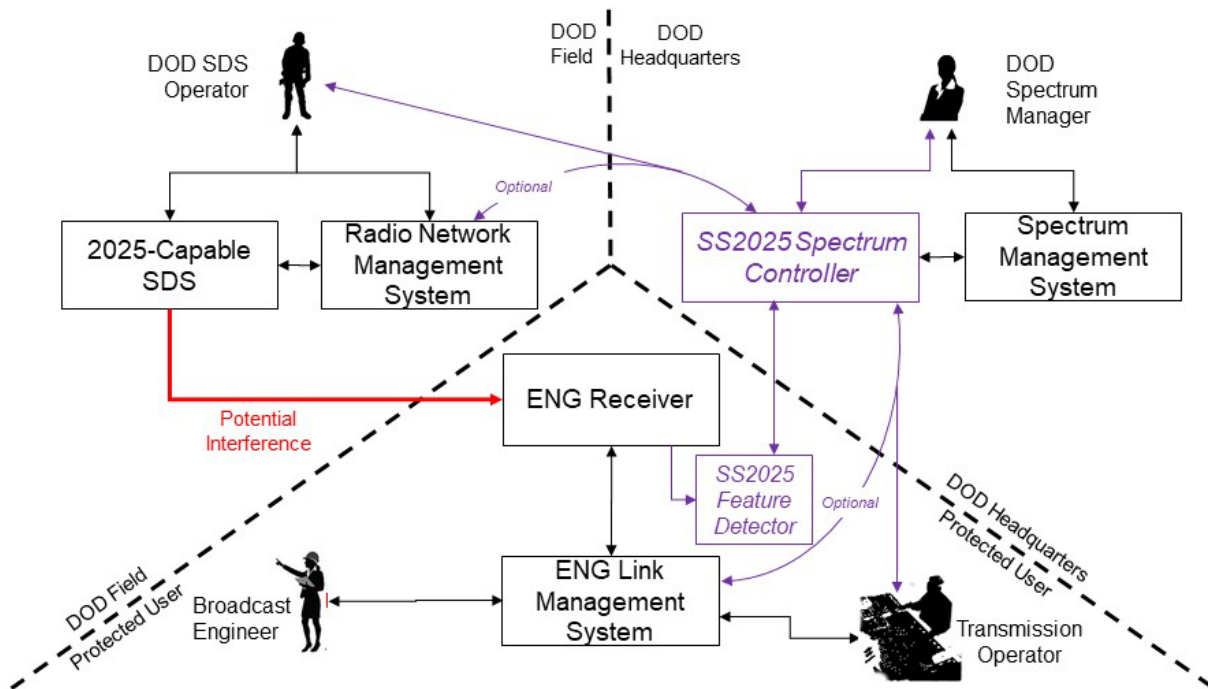


Figure 16: Complete DSA system for Interference-Measurement-based DSA.

This DSA system requires communications between the DSA sensor (located at the ENG receiver) and the DSA control processor. The DSA control processor implements a reasoner and all other methods needed to modify system policies. The DSA control processor also communicates with the DoD control systems necessary to manage DoD assets. Figure 16 is a notional diagram of the complete DSA system for Interference-Measurement-based DSA. The figure illustrates three components of the DSA system. The incumbent ENG system is depicted in the lower portion of the diagram. Observe that a Feature Detector has been included as an extension to the ENG Receiver. Observe also that the system includes an ENG transmission

operator responsible for pointing the high-gain ENG receive antenna and for assuring that the ENG links close with sufficient performance. The Feature Detector output is input to the Spectrum Controller which contains the reasoner and all necessary DSA policies. The reasoner output is input to the DoD spectrum manager who is the authority regarding DoD system spectrum use. There is an optional human in or on the loop depending on the level of automation between the Spectrum controller and the DoD Spectrum management system. The DoD Spectrum Manager forwards spectrum decisions to the DoD spectrum dependent system operator who manages actual DoD operating parameters. The humans in this loop may be removed in future systems as the DSA cooperation technology is proven.

5.4 Approach 4: Distributed Spectrum Sharing Incumbent Informing Capability (IIC) Application

This section advances a method that would greatly improve national spectral efficiency through a near-real time spectrum coordination mechanism designed specifically for incumbent system operators using their existing spectrum-dependent systems without modification. An application designed for smartphone, tablet or other Internet-based user equipment would greatly facilitate increased spectrum sharing for radios, radars and other user equipment between enterprises that have very little operational reason to coordinate their operations. Such an application would facilitate sharing with lower link margins and process overhead than today's more static deconfliction planning methods.

An initial use case for a purpose-built application for heterogenous spectrum dependent system incumbent informing capability (IIC) would provide frequency operations deconfliction between military radio, radars, TDLs and commercial point-to-point radios used by the Broadcast industry for ENG and other entertainment content requiring live backhaul over the BAS spectrum to a central facility from which over-the-air broadcast television and radio signals are transmitted.

The SMCS portal that is developed by DISA-DSO is designed to connect the various military organizations planning and conducting operations as co-primary users in the BAS bands dedicated for ENG use. The FCC has made clear that while DoD enjoys co-primary status, DoD has the full onus to ensure that DoD system operations do not interfere with ENG incumbent use of the BAS band. The SMCS Portal serves as a repository for registered ENG operators and terminals, geographic limitations on DoD BAS Band operations, spectrum management and organizational contact information for military radio, radar and tactical data link operations. The portal replaced an e-mail coordination workflow whose 'time-late' nature and inherent ambiguities contributed to skepticism in the ENG community leading to resultant risk-averse protection of BAS with lower overall spectral efficiency. The Portal improves upon DoD coordination but will be sub-optimal without a complimentary coordinating mechanism for the ENG Broadcast community of interest (COI). The proposed Application will provide such a coordinating mechanism that is low cost, has a low barrier to entry, leverages widely available commercial wireless infrastructure and would provide affirmative feedback that 'just in time' BAS channel use notification is received, understood and acted upon by potentially interfering DoD emitters. The distributed share situational awareness afforded by the SMCS Portal and the proposed BAS IIC Distributed Application should result in reduced time and area protection declarations by the ENG COI, increasing the available periods of operations for military radio, radar and TDL use.

The Spectrum IIC Distributed Application will have extensible utility in other shared bands, as governments continue to make legacy spectrum bands available for 5G and other new wireless systems. In some cases, the application will provide optimal sharing coordination between enterprises, in others, it will serve as a useful stepping stone for automated dynamic spectrum

sharing (DSS) that will be designed into future systems. The metadata collected by the IIC Application will support DSS system development and generate useful confidence building between organizations with disparate missions and business objectives.

The IIC Application for BAS deconfliction will support ENG operations in the field, in fixed sites, mobile ground stations and airborne BAS transmissions. The IIC Application will pre-register BAS operators and their radios with the DoD operated SMCS portal. It will collect definitive information on Channel Use (frequency), Antenna Selection (omni, directional, fixed, mobile), Antenna Orientation (azimuth or azimuth range), Time, Geo-location and use the collected data to generate protected BAS volumes in a temporal format that will support ‘just-in-time’ coordination with DoD. The IIC Application will additionally support identification and rapid resolution of harmful interference between authorized BAS transmitters of differing co-primary priority status. The ENG community will be able to rapidly communicate a ‘cease buzzer’ direction to DoD through SMCS should the de-confliction mechanism encounter an inappropriate transmission. In the future, DoD may find that the IIC Application used on military 5G user equipment will also enhance SMCS utility and provide out-of-band local validation for SMCS military system operations. The APIs used for the application would support simple integration with future radio, radar and TDL equipment and a wide range of Internet of Military Things (IoMT) wireless protocols.

APP-based Approach for Incumbent Informing Capability

Recently, IIC for Time-Based Sharing has been proposed as an innovative way to increase opportunistic spectrum access collaboratively, securely, and dynamically within spectrum allocations principally used by the federal government [11]. The IIC is a mechanism for more reliably informing “new entrants” in a shared spectrum band when incumbent federal systems are operating in close proximity and thus need to be protected. New entrant access to the spectrum would be controlled through an enhanced, near-real-time Spectrum Coordination System (SCS). The IIC could enhance extra layers of sharing techniques such as the ESC capability, which presently is required by the FCC for the CBRS in the 3550-3700 MHz band.



Figure 17: Incumbent Informing Capability Concept.

IIC is a time- and location-based sharing approach that would enable DOD and other federal spectrum users to submit information, reliably and securely, about when and where they would be employing certain frequencies. This information then would be fed into a spectrum coordinating system (SCS) to temporarily modify the operations of the other lower priority users sharing the

impacted bands. The goal is to enable more efficient, secure, and reliable spectrum sharing between 5G networks and the incumbent federal radars and could be scaled to other spectrum bands.

This IIC concept further achieves the priority of creating an enduring process for spectrum access. Even though NTIA is required by law to prioritize exclusive use when feasible, sharing may be used instead when relocation of federal systems would take too long or cost too much. In addition, because spectrum is a limited resource and everyone’s spectrum access requirements are increasing, relying exclusively on system relocation is not sustainable. Spectrum sharing is a necessary tool to meet repurposing goals and to ensure all users have sufficient spectrum access.

Figure 17 shows the IIC Concept as defined by the NTIA White Paper. IIC originates from the Federal Spectrum Operator (e. g. Radar) and the information is logged into an SCS (e.g., Spectrum Access System – SAS). A Commercial Operator would then access the SCS on a regular basis to check if they are allowed to use the spectrum in a particular Geographical Area at a given time.

The same IIC approach should work in other spectrum bands such as 2025 – 2110 MHz where Federal systems would like to share the spectrum used by the Broadcast systems. In this band, the information flow will be from the Broadcasters to the Federal Systems, since Broadcasters are the incumbents.

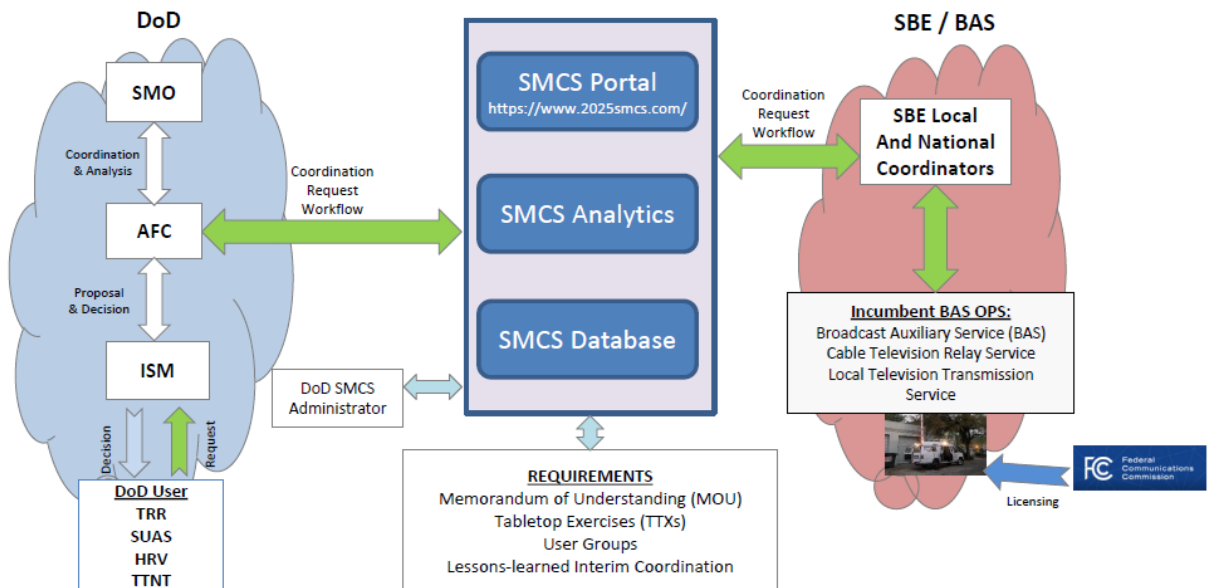


Figure 18: Current approach to the Spectrum Management Coordination Portal (SMCS) as defined by DISA-DSO.

Figure 18 shows the current architecture for spectrum sharing in the 2025-2110 MHz Band. The SMCS portal is used to coordinate between the Federal Systems (e.g., TRR, SUAS, HRV, TDL) wanting to use this spectrum and the Broadcast system having incumbent operations in this Band. Operators of the Broadcast systems such as ENG, need to register into the SMCS Portal and inform the Database of its current use, or planned usage. Since news may happen at any time and at any place, such an approach where operators need to log into the portal and add the information is cumbersome and may not scale.

Figure 19 shows our proposed APP-based approach to spectrum sharing. Such an APP may be downloaded to the mobile phones of the operators. The recommended APP-based approach is a way to orchestrate the IIC from the Broadcasters (Commercial) to the Federal Systems. Such an approach provides a faster Machine-to-Machine spectrum sharing by leveraging well developed and secure API calls. In contrast to a user interface, which connects a computer to a person, an application programming interface connects computers or pieces of software to each other. The calls that make up the API are also known as subroutines, methods, requests, or endpoints. An API specification defines these calls, meaning that it explains how to use or implement them. One purpose of APIs is to hide the internal details of how a system works, exposing only those parts a programmer will find useful and keeping them consistent even if the internal details later change. An API may be custom-built for a particular pair of systems, or it may be a shared standard allowing interoperability among many systems.

The operator wanting to use the 2025 MHz – 2110 MHz spectrum, brings up the APP on the phone and punches in three to four key pieces of information which are conveyed to the SMCS Portal via API calls. The information to be entered in the APP may be: 1. Broadcast LIVE, 2. Location of the Operator, which may be captured from the location service of the device itself, 3. Channel that is being used by the Operator, 4. Direction of the ENG Antenna, based on the location of the operator and the fixed location of the ENG base station.

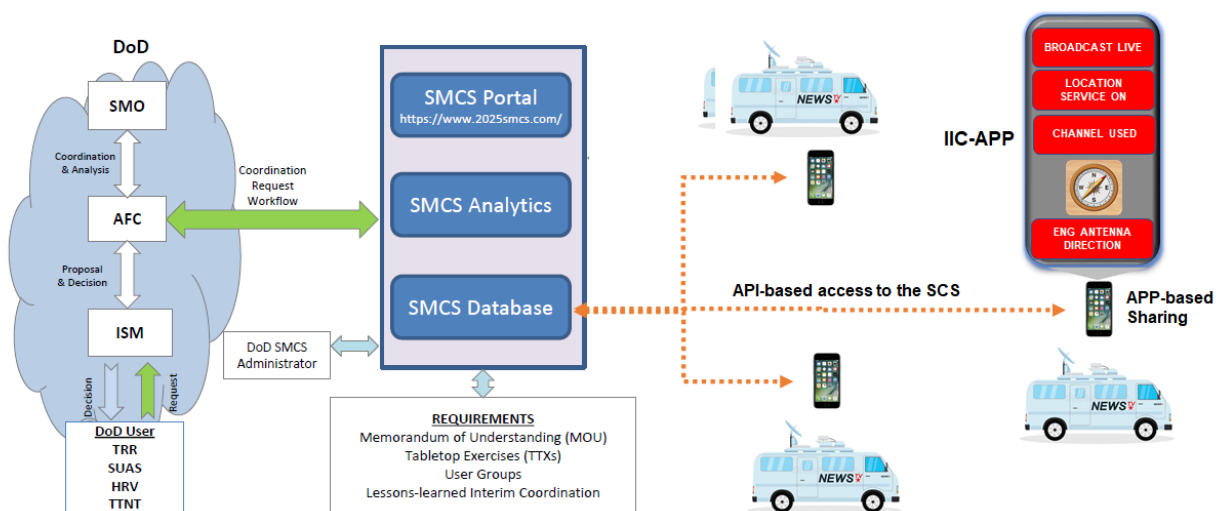


Figure 19: Proposed APP-based spectrum sharing approach.

This technique of APP-based IIC may also be used for other frequency bands such as 3.1 GHz to 3.7 GHz.

5.5 Security and Cybersecurity Recommendations

The recommended practice for coexistence between TDLE and ENG envisions a reliable and effective spectrum system that is invulnerable to cyber-attacks in a hostile operational RF environment. Figure 20 provides a taxonomy of potential Cyber-attacks on TDLE-ENG spectrum coexistence. Cyber-attacks may take different forms in a DSA-based spectrum sharing environment, as summarized below:

- Denial of service (DoS) attacks or jamming where a malicious adversary floods the information sharing infrastructure with overwhelming spectrum request traffic with the intent to disrupt DSA operation. In beacon-based spectrum sensing technique, a jammer may flood the control

channel with malicious beaming signal to incur DoS. Another form of DoS attack is where a malicious adversary compromises an ENG system to disrupt DSA operation.

- Spoofing where malicious adversaries masquerade as TDL or ENG system to disrupt reliable spectrum sharing
- Spectrum sensing data falsification attack where a malicious adversary injects false sensing information to degrade decision-making capability of TDL systems. In beacon-based spectrum sensing, a malicious adversary may inject unauthenticated beacon signal into the channel
- Primary User Emulation (PUE) attack. PUE is covered broadly in the Cognitive Radio literature as it is one of the most detrimental attacks on spectrum sharing systems. PUE is a spoofing attack where a malicious user mimics characteristics of ENG systems to severely degrade TDL-ENG spectrum coexistence.
- Privacy attacks where malicious adversaries exploit vulnerabilities in SAS/spectrum database to infer information that might reveal protected information.

As shown in Figure 20, cyber-attacks exploit vulnerabilities at the PHY-layer, MAC-layer or the network layer. Furthermore, sophisticated cyber-attacks may exploit a combination of lower layer protocol vulnerabilities to degrade DSA operation at a higher protocol layer. To enable reliable and effective TDL-ENG coexistence, it is critical to address cybersecurity risks in DSA mechanisms and the underlying spectrum information sharing infrastructure.

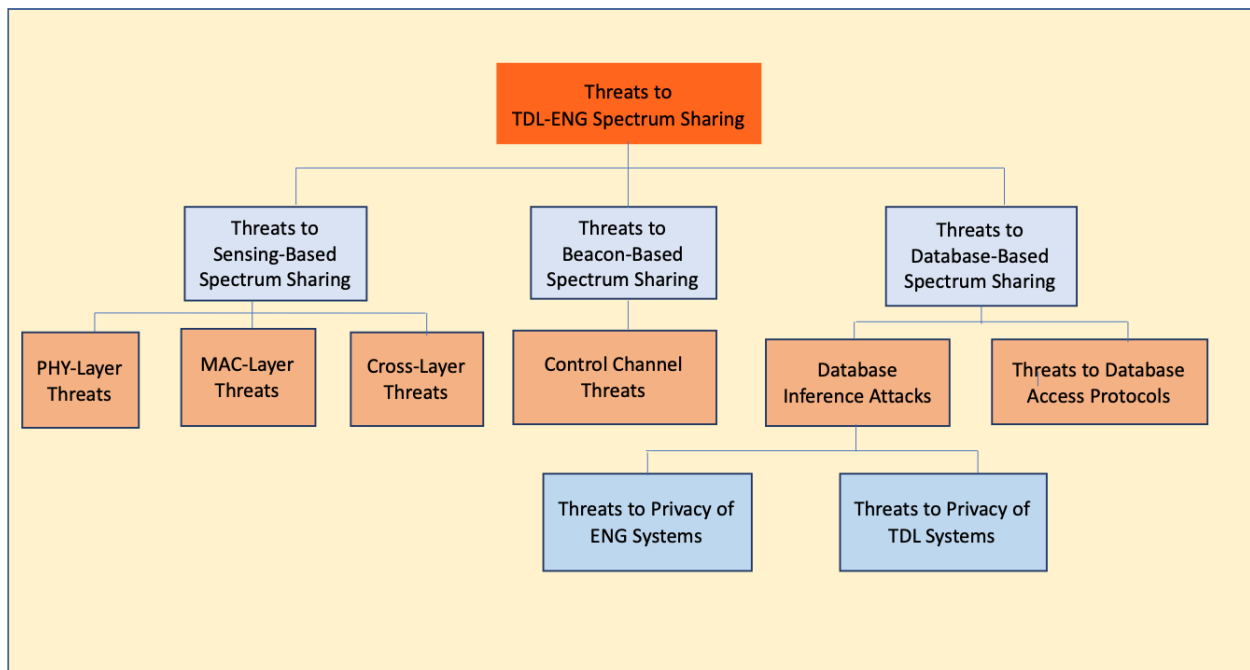


Figure 20: Taxonomy of Cyber-attacks on DSA Systems. Figure adapted from [26].

The Recommended Practice for TDL-ENG coexistence should include security and enforcement requirements [26]. The authors in [26] provided a summary of the Confidentiality, Integrity, Availability, Authentication, Compliance, Access Control and Privacy requirements that can potentially apply to TDL-ENG spectrum sharing scenario:

- Confidentiality: Along with the data stored in the database, the data communicated between TDL systems and the database should not get disclosed to unauthorized users.

- Integrity: The data stored in the database and communicated among TDL systems should be protected from malicious alteration, insertion, deletion, or replay.
- Availability: TDL and ENG systems should have access to the database and/or the spectrum when it is required.
- Authentication: The TDL-ENG spectrum sharing components, including the database, and the TDL and ENG systems should be able to establish and verify their identity.
- Compliance: Any non-compliant behavior resulting in harmful interference should be detected by the TDL systems.
- Access Control: No TDL or ENG user should be allowed to access the database or the coordination system without proper credentials.
- Privacy: Sensitive or private information of the users on either side should be properly protected.

Using the IIC Application proposal as an example, requiring Broadcasters to implement strong cybersecurity programs commensurate with DoD strength implementations, is probably unaffordable and would defeat the purpose of the inexpensive, rapidly deployable solution with broad utility across a wide range of commercial companies not under contract to DoD. Beacons and other proposals relying on non-government equipment would be similarly challenged. Given that limitation, the IIC application would probably want to employ multifactor authentication and a strong identity registration mechanism under DoD control. Cybersecurity risk mitigation solutions need to be an included implementation task as proposals move from concept to design.

5.6 Measurements and Evaluation Recommendations

The biggest threat to coexistence of TDL and ENG systems is interference between the two systems or illegal transmissions that interfere with legitimate transmissions. These signals can be periodic or may be present at different frequencies over time, making the discovery and removal of these sources of interference a significant challenge. An indicator of interference is a high noise floor in the receive channel. Interference naturally affects reception first, where the signal levels are normally small. A key point is that an interfering signal does not need to be on the receive channel to cause interference. It only needs to be within the receiver's bandwidth, which normally means that it only needs to get past the receiver's pre-filter. Once an interfering signal is present at the input of a receiver, it affects the receiver's front end, causing a reduction in sensitivity. This will cause the effective carrier-to-interference ratio (C/I) to be lower and result in all the symptoms of a weak signal (noisy, waterfall effect, low data rate, dropped calls), except that the received signal strength measurements will be strong due to the high noise floor. This interference mechanism is called Receiver De-Sensitization, or Receiver Desense. In extreme cases, it can even result in Receiver Blocking.

Once the interfering signal is spotted, it is important to characterize the signal before disconnecting from the receiver's test port. Various spectrum analyzer functions are available to ensure that this signal can be characterized so that one can recognize the same signal if seen in another context. Some signals may be intermittent. Hopefully, they are periodic, or at least repeat with some discernible pattern.

There are several mechanisms that can cause interference to ENG systems. Interference can be directly on a receive channel, in a receive band, originate as a harmonic, or come from passive intermodulation. In addition, it can be due to impulse noise or a near-far effect. Other common sources of interference include leakage from signals distributed on RF cable, such as cable TV or Last Mile signals, or even cordless phones. Knowing specific mechanisms that cause interference will help spot/stop interference in the field. Before we investigate these mechanisms

one at a time, we provide some details about polarization aware receivers, of which ENG receivers are an example.

A polarization aware receiver includes the following components as shown in Figure 21. It has a dual polarization 2 port antenna, two pre-selectors and LNAs, and a coherent 2-port receiver. With this kind of receiver, the incident Signal of Interest (SOI) is received by the orthogonal pair of antennas. When the incident orthogonal SOIs are summed using coherent combining (MRC, MMSEC, etc.), PDL is eliminated. In addition, since the noise in both receivers is uncorrelated it will not sum coherently thus an SNR improvement is realized.

If there is a dominant interference signal in the channel, which in a single receiver would set the Signal-To-Interference Ratio (SIR), that interference will also undergo combining based on the solution determined by the SOI. If the incident interference were by chance cross polarized with the SOI, the combining will suppress the cross-polarized interference signal thus improving SIR.

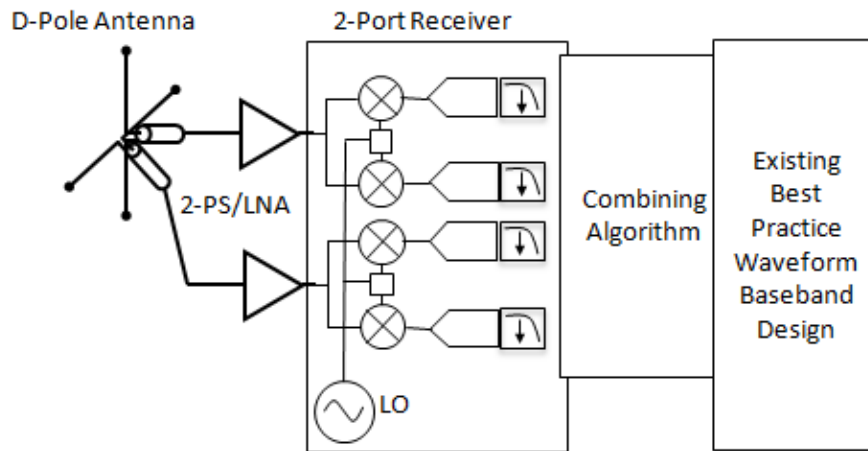


Figure 21: Polarization aware receiver.

Combining algorithms that optimize SINR for the SOI in the presence of noise and interference [27] are now commonly used in modern communications systems.

We now describe a few mechanisms that can cause interference to ENG systems.

On-Channel Interference

This can happen to broadcasters due to channel assignments that are close in frequency while also being geographically close. ENG transmitters are typically located in remote locations far away from the news stations and require their directional antennas to be pointed back to the receive site or repeater. The receive antennas at the receive sights also must point their antennas in the direction of the transmit stations or repeaters. When multiple remote sites are reporting back to the same receive site or if a remote station is pointed in the wrong direction, there is potential for on-channel interference.

Passive Intermodulation (PIM)

Another common cause for in-channel interference is passive intermodulation (PIM), which can come from within the victim antenna system or from an external source. This is also called the Rusty Bolt Effect. It is caused when two or more strong RF signals combine in a non-linear device, such as a transistor, diode, or even the crystals found in corrosion or rust. This corrosion may even be outside the radio system. It can be caused by a rusty fence, rusty bolts, corroded rooftop air conditioners, or even a rusty roof. Of course, it is also possible that loose or dirty connectors in an antenna feed line or poorly configured transmitters may also be the cause. PIM requires at least two strong signals and a non-linear device of some sort. Once generated, PIM frequencies are very predictable. If you have two original frequencies, F1 and F2, the third, fifth, and seventh order intermodulation products will be found equally spaced above and below the two original signals. For instance, if the two original signals are at 2060 and 2070 MHz, other PIM products will be found at 2080, 2090, and 2100 MHz. They also will be found at 2050, 2040, and 2030 MHz. There are many cases where legitimate transmitters can produce PIM that falls into another radio's receive band.

In-Band Interference

As noted earlier, interference does not need to be on the receive channel. If the interfering signal is within the pass band of the receiver's receive filter, that is often sufficient to cause receiver Desense. These signals can come from Carrier signals of other services, Intermodulation products and Harmonics of other signals. The key point is that a signal does not need to be on the receive channel to cause interference. It only needs to make it through any receive filter to the front end of the radio receiver.

Near-Far Problem

The Near-Far problem is the RF equivalent of two people trying to talk across the room at a loud party. The surrounding noise tends to make conversation difficult or impossible. In the case where a wide area RF coverage is overlaid with a smaller area coverage, and the two operating frequencies are close enough to give receivers a problem, the nearby, in-band-but-off-frequency signal can overload a receiver trying to listen to the weaker signal. In Figure 22, the green lines represent field strength of the respective transmitters.

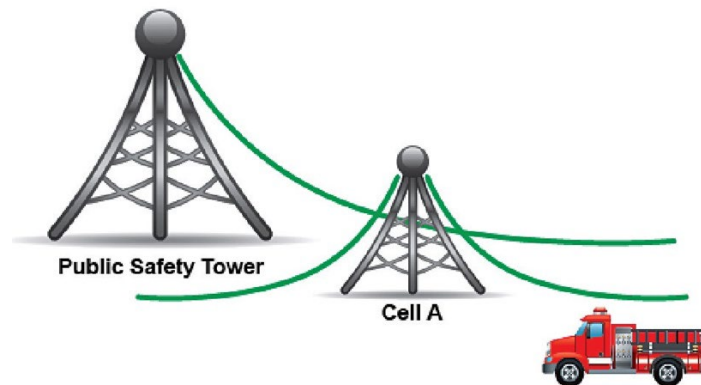


Figure 22: Near-Far problem in the context of public safety.

In this case, the fire truck is trying to listen to the public safety signal but has a radio receiver that is overwhelmed by the nearby cell tower signal. Two conditions must be present for this to happen: 1) The interfering carrier must have a frequency that is passed by the receiver's pre-filter and 2)

The interfering carrier must be strong enough to Desense the receiver. Solutions might include adjusting transmitter frequencies or improved filtering on the fire truck's radio receiver.

The near-far problem can also happen between cell towers as shown in Figure 23, as long as the cell phone cannot make a handover. This may be the case near the edge of a metropolitan market where a cell phone of carrier "A" is broadcasting a strong signal to reach the distant cell tower of carrier "A." If there is then a cell tower operated by carrier "B" near that phone, the "B" carrier receiver may be temporary Desensed by the loud Phone "A."

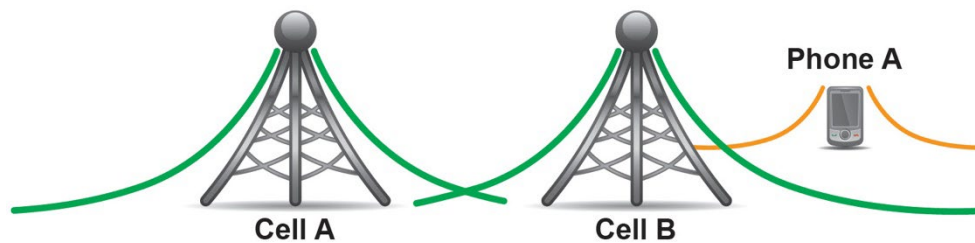


Figure 23: Near-Far problem in the context of cell towers.

Intentional Interference

Some sources of interference are intentional, for example "Cell Phone Jammers." Regulators take a dim view of this practice, as you would expect. Jammers can be found in shopping malls, where employers want to ensure employee productivity, in cars, or even in military bases. Civilian use of jammers is generally illegal. In the United States, the FCC has taken legal action on companies selling cell phone jammers, citing potential harm from interfering with emergency communications. There are a wide variety of scenarios that can cause intentional interference.

For the purposes of the Dynamic Spectrum Sharing, the types of interference that are relevant are the On Channel and Intentional Interference mechanisms with the intent to change channels to unoccupied spectrum when the ENG beacon or ENG transmission is sensed. In the rest of this section, we provide specific test recommendations for the laboratory and field environment.

Specific Test Recommendations for the Laboratory

Although there are several options being put forward on how to most efficiently share the spectrum between the ENG and TDL systems, the common thread between them is that the TDL radio have the ability to detect the ENG signal using overlapping channels and switch channels before the TDL transmissions exceed the interference threshold of the ENG system. In this scenario, there are two parameters that need to be measured and achieved, sensitivity and duration. The sensing radio will first need to detect the signal of concern, then reach a signal threshold for a certain duration before actively changing transmission parameters.

In order to make accurate measurements, it is critical to establish a test environment with an RF noise floor at least 15 dBm below the RF signals under test. This ensures that external RF energy doesn't impact the measurement and enables the test equipment to be configured for increased RF sensitivity. When devices are connected via an RF cable, external RF energy is blocked from both entering the test setup and leaking out of the test setup. Figure 24 describes the block diagram of a self-contained, low noise floor setup, where the two radios and spectrum analyzer are connected via cables, combiner, coupler and attenuators.

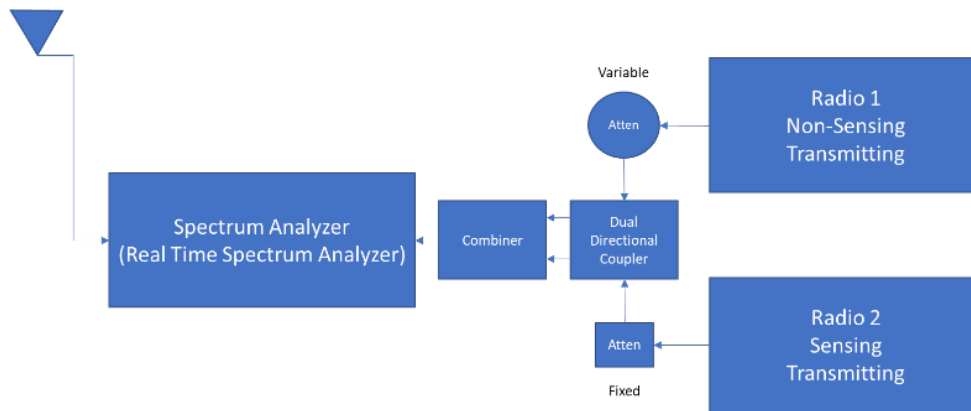


Figure 24: Laboratory Bench Test Scenario.

The primary objective of this test is to measure and validate the actions of the sensing radio (Radio 2) in the presence of another device transmitting on the same RF frequency or TDL channel. To accomplish this, both radios will transmit at their normal operating power levels. Radio 1 (or a Vector Signal Generator for initial testing of only the TDL radio) will have a manual RF power attenuator in line, allowing the tester to increase or decrease the RF power that the sensing radio (Radio 2) receives.

Having both radios connected to the same Spectrum Analyzer allows both transmitters to be monitored at the same time. With this test configuration, it will be visibly noticeable within the Real Time Spectrum Analyzer feature, at what point in time the sensing radio moves off the occupied channel and at what amplitude level of the ENG signal the transition occurs. Based on the current proposal, this level should be no greater than -108 dBm.

Another test parameter is the time it takes for the signal to move from the occupied channel to the available spectrum space. The transition time to the new RF frequency can be measured from both a reaction and transfer/settle time. The reaction time is defined as the time it takes for the radio to sense the power violation, determine it needs to move and then stop transmitting on that channel. The transfer/settle time is defined as the time it takes the radio to stop transmitting from the occupied channel and become stable on the new frequency. All three of these metrics, namely, power, reaction time, and transfer/settle time will determine how much communication is impacted on both systems (ENG and TDL).

Because the reaction and transfer/settle time should be extremely fast, it will be necessary to capture the IQ data and perform post processing analysis to determine accurate values. IQ data is the raw RF waveform data and can be collected on a Real Time Spectrum Analyzer (RTSA) with streaming capability. The entire ENG channel plan spans the 85 MHz from 2025 to 2110 MHz, so a spectrum analyzer with a wide IQ capture bandwidth is needed. We recommend using a spectrum analyzer with at least 110 MHz IQ capture bandwidth that includes 12.5 MHz adjacent spectrum coverage on both sides, to allow visibility to noise floor fluctuations due to external interference mechanisms.

Once the IQ data has been captured during a frequency change, the collected data needs to be analyzed in order to measure all of the metrics of interest including power, reaction time and transfer/settle time.

Specific Test Recommendations for the Field

Once the radio(s) basic spectrum sharing performance have been verified within the controlled lab environment, they will need to be tested in the field. Testing in the field will introduce a new set of variables which include radios in motion, external RF energy and a noise floor rise. Figure

25 describes the block diagram of a field test setup, which includes spectrum collection tools with the radio. This test setup would be duplicated for both the TDL and ENG radios to collect spectrum data from both radios, since they will no longer be in close proximity to each other. This configuration can be placed in either a stationary or mobile environment, but the test plan should progress from stationary to moving experiments.

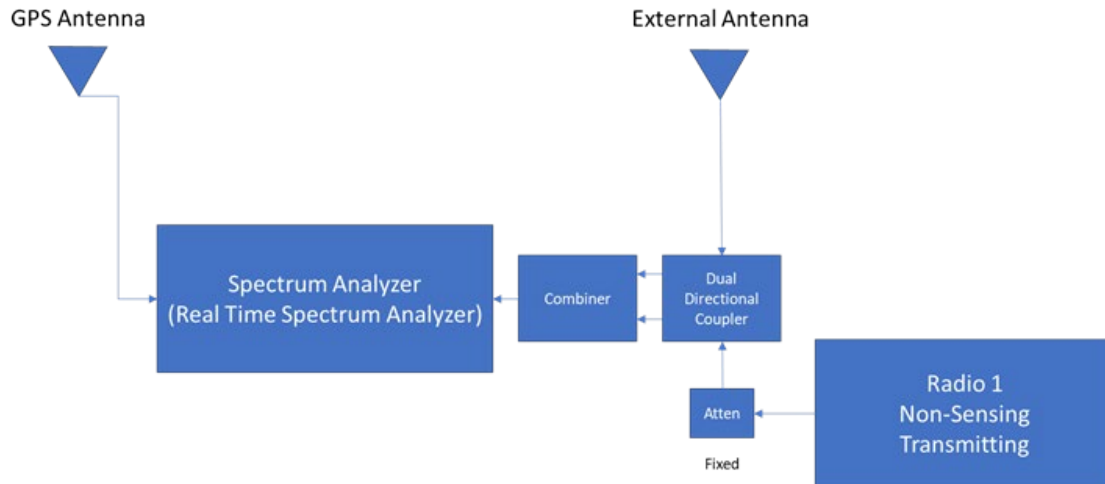


Figure 25: Field Test Scenario.

Utilizing the Bench Test Scenario thresholds and spectrum analyzer configuration, the same set of tests will have to be performed. The non-sensing radio is now external to the system and therefore an additional variable. Because the radios have already been verified to behave properly or within a specified manner, the goal of the field test is to verify that external factors don't impact the operation of the sensing radio(s) and the assumptions on thresholds and other environmental factors were correct and the TDL radio is able to sense the ENG radio and switch channels without violating the interference threshold.

Since the field could have out of band transmitters, having a broader RF monitoring system is important. These systems use spectrum analyzers left at a location, or locations, for a period of time. This can be as simple as setting up a handheld spectrum analyzer to record traces and checking back in a week, or as focused as using dedicated rack mounted analyzers in combination with networked software to continually characterize the spectrum and locate interference sources. A dedicated remote spectrum monitoring system should consist of at least 3 remote spectrum monitors spaced around the field test range area. This system should be recording spectrum activity within and adjacent to the DRL Channel Plan.

Testing the sensing radios in the field while mounted on a moving platform or vehicle, a GPS time and location stamp solution will be beneficial. This will allow the measurements to be stamped with both time and location information. This information can be used for post analysis work and/or proof of measurement data.

In order to capture signals that occur just before and just after an event, pre-triggers will need to be used. These automate the process and help ensure that all events of interest are captured. The pre-triggering will have to be configured based on the results of the Bench Test Results.

Once the field test measurements have been made, the data will have to be post processed and compared to the Bench Test Results. The data captured with the broader RF monitoring system, which was active during the field testing, will have to be used to both verify field results and help



understand any anomalies between the Bench and Field test results. If it is found that the interference threshold of the ENG receiver was violated at any point during the testing, analysis of the data should be used to determine the parameters that need to be changed prior to rerunning the field experiments to prevent violation of the ENG system limits.

5.7 Summarized Performance of Proposed Approaches

This section provides a blueprint for developing use cases and defining requirements for MIL-CIV spectrum sharing, which can easily be extended to other paradigms. These requirements will include but not limited to the location(s) of the receivers for the incumbent ENG system, the radio equipment type(s) and platforms used by the incumbent. The requirement will also have to take into consideration the DoD system requesting access to the ENG spectrum. Coexistence parameters may be part of the specification or may be calculated as part of the TDL-ENG sharing-system design. Coexistence parameters will include a minimum acceptable SINR and time constraints defining the maximum time durations that SINR bounds must be achieved. In most cases the location of the ENG transmitter(s) as well as the location of the DoD system of interest is variable and may have to be specified statistically.

Table 3 summarizes at a high level, the expected performance associated with each of the proposed spectrum sharing approaches. The Geographic Database approach has the lowest implementation cost and can be used with ENG receivers in remote areas (far from TDL operations); however, it is impractical to use this approach by itself in dense urban areas. The Beacons and Sensing approach through DRL, Centralized Database and Distributed Sensing approach, Direct measurement of Interference at ENG receiver and Distributed Spectrum Sharing IIC Application are all viable approaches with different implementation costs and will provide different amounts of spectrum availability.

Table 3. Constraints associated with each Spectrum Sharing Approach

|  Approach  Constraint | Geographic Database approach (Baseline) (Section 4.2) | Beaconing and Sensing through DRL (Section 5.1) | Centralized Database and Distributed Sensing (Section 5.2) | Direct Measurement of Interference at ENG Receiver (Section 5.3) | Distributed Spectrum Sharing IIC Application (Section 5.4) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Cost | - Need to Install a real-time connection from TDL receiver to a centrally located system to process and apply information in real-time | - Need to modify TDL radio system to support spectrum sensing and adaption - Need to integrate a beacon transmitter in the ENG receiver | - Need to Install a real-time connection from TDL receiver to a centrally located system to process and apply information in real-time - Need to maintain the freshness of databases | - Need to install a real-time connection from both TDL receiver and ENG receiver to a centrally located system to process real-time information - Need to install a spectrum sensing receiver near the ENG receiver | - Need to develop and operate a centrally located Spectrum Coordination System such as the one proposed by DISA to process information in real-time |
| Spectrum Availability - Reduction in the amount of spectrum for | Large uncertainties (propagation loss, antenna patterns, | Minimal uncertainties | Large uncertainties (propagation loss, antenna patterns) | Medium uncertainties (associate measured signals with specific TDL platform) | Large uncertainties (propagation loss, antenna patterns, |

| | | | | | |
|------------------------------------------------------------|-----------------------------------------------------------------------------------|-------|------------------------------------------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------------------------|
| DoD use due to parameter estimation uncertainty | operating period) | | | | operating period) |
| Security | - Need to provide TDL operational data (location, altitude, use period) to public | | | - Need to provide detailed TDL waveform information to public | - Need to provide TDL operational data (location, altitude, use period) to public |
| Interference – High interference to ENG receiver | | | Significant interference to ENG receiver with highly directional antenna (hidden node problem) | | |
| Timescale for Coordination | Long | Short | Short | Medium | Medium |

Because there may be statistical variation in the requirements definition, a statistical performance metric may have to be defined and used in comparing problem solutions. The details of appropriate performance metrics are described in various sections throughout the document including Section 4.4, but these metrics are usually specific to a use case and will have to be detailed during system design.

To summarize, the process for spectrum sharing could be as follows:

1. Define the use case(s) of interest.
2. Define the performance metric appropriate for the use case(s).
3. Define a set of potential spectrum sharing architectures. These architectures may be based upon the approaches discussed in Section 5.
4. Evaluate the performance metric for each of the considered sharing architectures.
5. Estimate the cost for each of the considered sharing architectures.
6. Select a sharing architecture and method(s) based on the trade space between performance and cost.

6. Conclusion

We conclude by noting that this document has provided multiple recommendations for efficient spectrum sharing between TDL and ENG systems, that include direct sensing, distributed sensing, beaconing, databases and even utilizing the incumbent Informing Capability. We have provided security and cybersecurity recommendations and described ways of measuring and evaluating interference. We have also summarized the cost versus performance tradeoffs of the recommended approaches, and observed that based on the use case, the best performance is often obtained by one or more likely a combination of the sharing approaches highlighted in this document.

7. Informative Annex

7.1 Annex A: Review of Electromagnetic Polarization

The polarization of an electromagnetic wave is defined by the orientation of the wave's electric field vector. It is important to understand that polarization is a fundamental property of the EM wave and it can be, and has been, exploited in two or more port/antenna systems for spectral efficiency, increased link reliability and interference mitigation. If polarization is ignored, as it often is in RFSA and DSA sensing systems, large errors in reported power can result due to sensing receiver cross polarization with the incident signal of interest, resulting in failures to detect ENG transmissions thus violating spectrum sharing agreements.

Optical communications engineers are often taught mathematical formulations for electromagnetic polarization using Stokes parameters developed by George Stokes in 1852 and rediscovered independently by Francis Perrin in 1942 and by Subrahmanyan Chandrasekhar in 1947. RF communications engineers are rarely introduced to EM polarization concepts although it is becoming critically important as spectral efficiency demands increase. For example, cataloging Stokes parameters of typical ENG antennas will be helpful in formulating and implementing spectrum sharing solutions for those systems.

- Poincaré Sphere
 - Linear polarizations on equator
 - Left Hand Circular Polarization (LHCP) and RHCP are special cases of elliptical polarization
 - Angle between any two polarizations, P_1 & P_2 given by α
 - Directly opposite polarizations ($\alpha=180^\circ$) are orthogonal

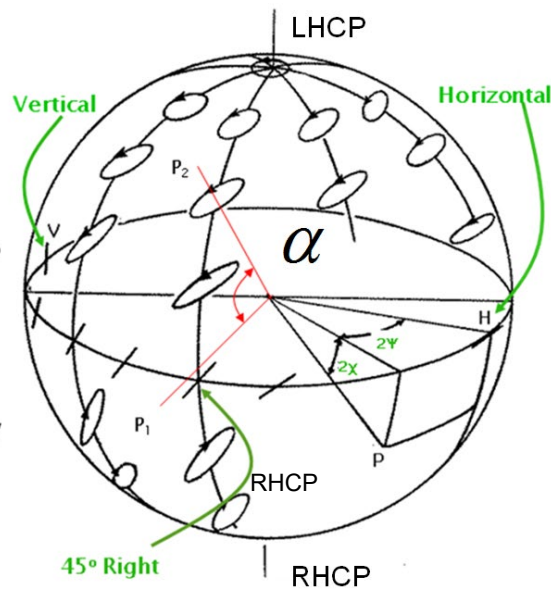


Figure 26: Poincaré Sphere Mapping of Polarization States

A convenient graphical description of polarization state was offered by Henri Poincaré in 1891 and is known as the Poincaré sphere as shown in Figure 26. We are used to specifying polarization as linear; vertical, horizontal, slant right and slant left as well as RHCP and LHCP. The Poincaré sphere helps us to understand that these six polarization states are only corner cases of an infinite number of polarizations states. The Polarization Dependent Loss between two antennas with polarization states P_1 and P_2 as shown in Figure 26, is given by Equation 1.

$$PDL_{P_1 P_2} = 10 \log_{10} \cos^2 \left(\frac{\alpha}{2} \right), \quad (1)$$

where α is the angle formed by two vectors originating at the center of the Poincaré Sphere and terminating on their respective polarization states on the surface of the sphere as shown in Figure 26. Point-to-point microwave links are able to double spectral efficiency (i.e transmit two independent data streams on the same frequency) by utilizing an orthogonal pair of polarizations (α equal to 180°) in the same antenna aperture.

The polarization filter response as a function of α , is illustrated in Figure 27. Note that if the system designer picks an antenna, which will have a specific polarization state on the sphere, there will be a corresponding cross polarized state at an α equal to 180° with results in 40-50dB of PDL. That selection of a particular polarization for the system ensures that all received polarizations that are 90° away will be received with a 3dB loss due to cross polarization. If α is greater than 143° , the PDL is at least 10dB. An α greater than 168° , results in at least 20dB of PDL.

For common linear polarization antennas whose polarization states are along the equator of the sphere, the relative orientation of the antennas in space is 1/2 of the angle around the Poincaré sphere. Thus, at an angle of 180 degrees on the Poincaré sphere (the cross polarized state) the antennas would be oriented 90 degrees to each other in space as we are most accustomed to visualizing their configuration. It is easy to fall into the trap of visualizing cross polarization as simply this 90° rotation as this does not apply to the vast array of elliptical polarizations illustrated on the Poincaré sphere.

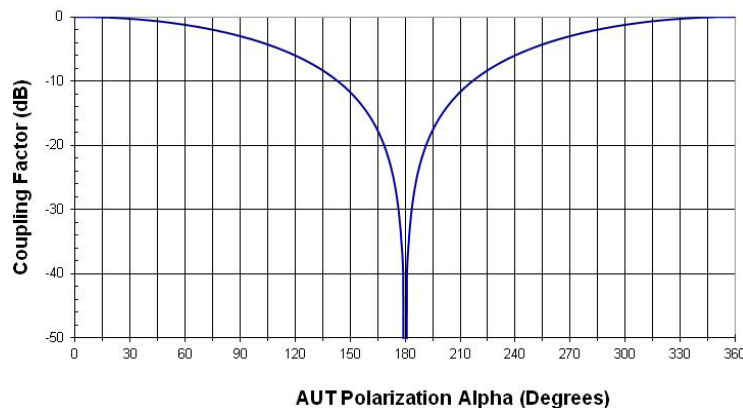


Figure 27: Polarization Filter Response

Polarization can be exploited to null interferers utilizing this filter response [28]. Adaptive polarization has an advantage over spatial array beamforming and null steering. If an interferer is on the same line of sight as the desired signal, as seen by the receiver, the spatial array cannot discriminate the interferer from the desired signal. In other words, if a spatial null is placed on the interferer, the desired signal is nulled as well.

Given the steepness of the polarization filter response, a polarimetric receiver can null the interferer on the same line of sight as the desired signal as long as the two signals have even a small difference in polarization. Unlike beamforming spatial arrays with multiple coherent

transceivers (4 or more ports for Az/EI beamforming), a polarimetric based DSA system can be implemented with a simple coherent two port transceiver in an omni-directional system.

If a radio network is operating in a highly scattered environment, one can therefore assume that a large distributed population of EMS emitters will arrive at the sensing system's single port receiver antenna with a uniform distribution of polarizations over the entire Poincaré Sphere then:

- 50% of the population will be reported with at least a 3dB error
- 10% of the population will be reported with at least a 10dB error
- 1% of the population will be reported with at least a 20dB error and may not be detected if close to or below the SA receiver's detection limit.

As a result, there is no single port magic antenna that can claim to provide EMS SA given these power measurement errors and the correspondingly low probability of intercept of ENG signals that could result in spectrum sharing violations. Given the ENG/TDL sharing agreement, all proposed sensing-based systems must implement polarimetrics with dual or triple polarization receivers.

Conversely, this realization allows us to conceive of a TDL systems that can intentionally transmit with a Low Probability of Intercept (LPI) by choosing a transmit polarization solution that is orthogonal to the ENG receiver polarization. This will result in significant (4x to 8x) reductions in the EZ/PZ radius.

Optimal Adaptive Polarization in Graphical Terms:

Any receive or transmit polarization can be implemented by controlling the relative phase and amplitude of two or three coherent transceiver ports connected to near orthogonal polarization antenna elements. Since this is a physical layer modification, any radio waveform can be upgraded in a fully reverse compatible fashion allowing polarization capable units to work with existing single port equipment. This is true for both TDL and ENG receivers.

Polarization base de-confliction methods described here can and should be utilized along with the other methods described in this document. For example, beamforming arrays implemented with adaptive polarization sub elements can implement both spatial and polarimetric processing. This system is referred to as a Space Polarization system.

Optimal Adaptive Polarization (OAP) solves for the optimal SINR for a desired signal in the presence of noise and interference [29]. In addition, OAP can be utilized to minimize interference to ENG receivers by ensuring that TDL signals are cross polarized with ENG receivers. The following examples should help the reader understand what this means to the TDL/ENG dynamic spectrum sharing system.

Let us say the TDL interferer is operating co-channel or adjacent channel to the ENG receiver and the TDL transmitter has knowledge of the ENG receiver's polarization [30], (i.e. from a coordination table, coded state via ENG DRL message, via measurement of a DRL message polarization if transmitted by the ENG receiver antenna, via measurement of ENG receiver LO feedthrough, etc.) as illustrated in Figure 28. It would make sense for the TDL transmitter to exploit the polarization filter response and move to an α of 180° to minimize the interference to the ENG receiver. Since the ENG receive antenna has the ability to be switched by the studio technician from RHCP to LHCP, as necessitated by a required building bounce or mountain bounce or marginal Non-Line-of-Sight path, this scenario can be reversed.

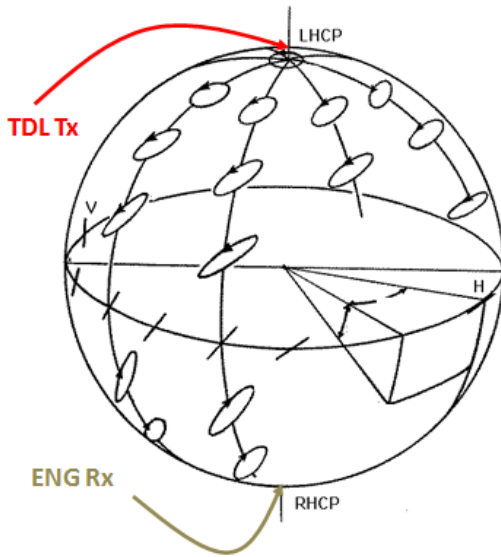


Figure 28: Maximum PDL De-conflicting TDL Tx from ENG Rx

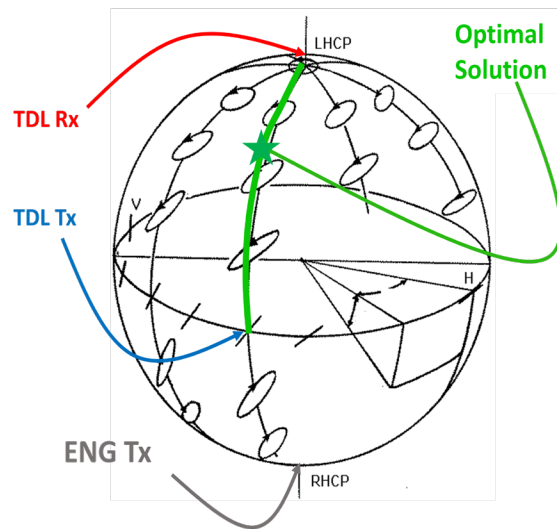


Figure 29: Optimal SINR for TDL receiver

In the case where the ENG transmitter is interfering with the TDL receiver, adaptive receive polarization can be exploited to perform anti-jamming and obtain the optimal SINR at the TDL receiver.

In the example shown in Figure 29, the ENG transmitter is RHCP. However, due to current test article geometry and local scattering, the TDL signal is arriving at the TDL receiver with right slant 45° . One might believe that the TDL receiver polarization solution should be LHCP to maximize the rejection of the ENG signal. This would indeed null the interferer; however, the desired signal is now 90° away from the receiver's polarization resulting in a 3dB desired signal loss. If this loss were to reduce the SNR of the desired signal below the threshold for proper decoding, the packet would be lost. In this marginal SNR scenario, the optimal polarization solution must lay along the arc from LHCP to the right slant 45° point. The compact and closed form solution for OAP solves for the precise optimal SINR receiver polarization for each desired packet that arrives at the receiver.

Antenna Pattern Considerations for Polarization:

As illustrated in Figure 30, a dipole antenna forms a toroidal (doughnut) radiation pattern. The pattern has transmission nulls along the axis of the dipole, a peak gain at the horizon when mounted vertically and a gain dependent vertical 3dB beam width ranging from $\pm 60^\circ$ to less than $\pm 5^\circ$ for collinear arrays. If an orthogonal polarization is to be achieved by simply rotating the dipole onto its side, the resulting pattern becomes highly directional with the transmission nulls now on the horizon. This pattern problem is sometimes referred to as a severe pattern fade.

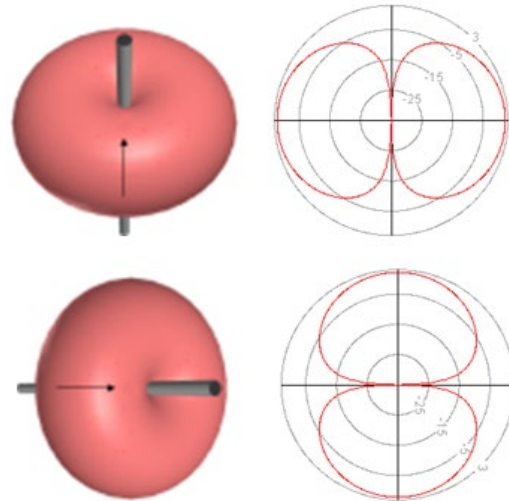


Figure 30: Dipole Antenna Pattern

It is therefore important to realize the required orthogonal antenna set with similar antenna patterns meeting the system deployment requirements.

Performance of Optimal Adaptive Polarization:

When OAP is implemented as an overlay on existing TDL waveforms, the spectral efficiency and interference rejection realized is significant. This has been demonstrated in previous efforts such as in [29].

For example, as shown in Figure 31, packet error rate curves are shown for un-coded narrow band physical layer packets in contested spectrum [31]. Switched Polarization Diversity (SPD) provides about a 9 dB advantage over a single antenna. Maximal Ratio Combining (MRC) adds another 3dB. However Optimal Adaptive Polarization (DP-MIMO on the graph) provides an additional 11 dB of SINR improvement over MRC for a total average SINR improvement of 23 dB over a single polarization antenna.

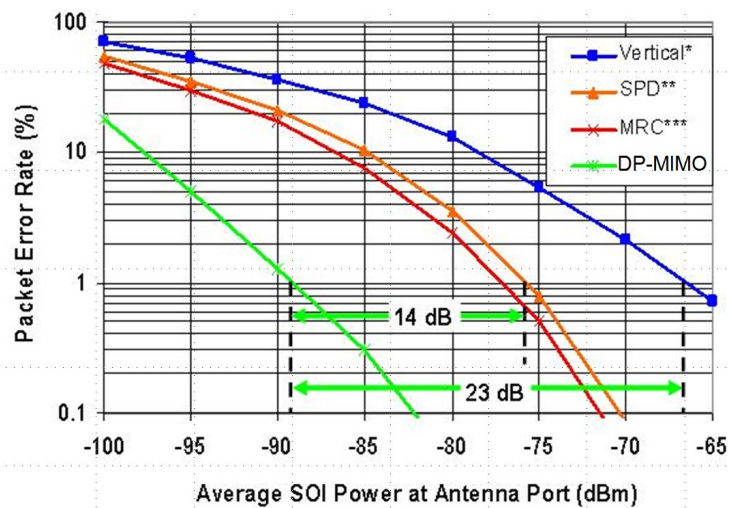


Figure 31: PHY Layer PER in Contested Spectrum

Since the polarization of a wideband signal is frequency dependent across its modulation bandwidth the apparent polarization of the signal will form an arc across the Poincaré Sphere. This is called Polarization Mode Dispersion (PMD) [32] as shown in Figure 32. Sub-band polarization solutions are computed across the bandwidth of the signal in the presence of dominant interferers who have their own PMD signatures and are thus mitigated by the algorithm [33].

Wide bandwidth modulation formats lead many communications engineers to believe that polarization, particularly in rich scattering environments, need not be considered as the polarization can vary greatly over the modulation bandwidth in a rich scattering environment and therefore a single antenna or a co-polarized Multiple-Input Multiple-Output (MIMO) array is sufficient for signal reception and transmission. Indeed, the PMD can vary greatly about the Poincare Sphere again as illustrated in Figure 32.

If the resulting amplitude response of the wideband signal with PMD is observed on a spectrum analyzer, with one antenna, the observer will often identify signal degradation across the bandwidth as multipath fading when many are actually attributable to polarization fades due to cross polarization with that single polarization observing antenna.

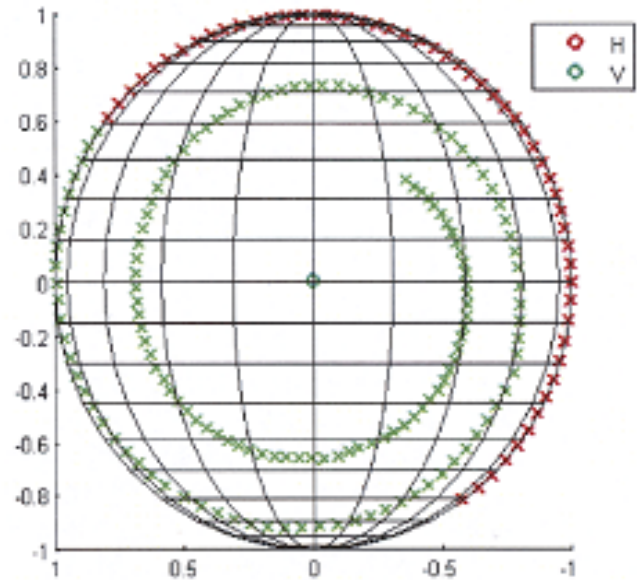


Figure 32: PMD for 200 received OFDM Subchannels

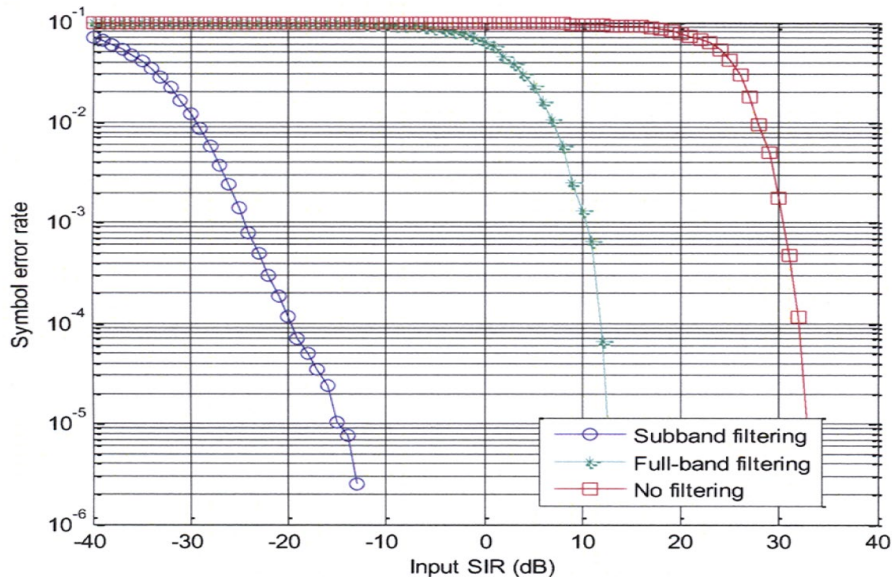


Figure 33: Wideband Polarization Sub-band Filtering

However, if one exploits PMD, just as MIMO exploits multipath, significant SINR improvements can be realized. In addition, significant improvements can be realized without the overhead of space time coding or beamforming. Wideband polarization sub-band filtering offers an additional 25-40dB of SINR improvements over full band filtering [34] as shown in Figure 33.

Some readers may be familiar with the so-called multi-polarization antennas. These antennas, like all single port antennas, produce a single polarization at any specific azimuth, elevation and frequency. Since the polarization pattern varies as a function of azimuth, elevation, and frequency, they produce some amount of PMD. It is also interesting to note that when these antennas are mounted on a conducting surface, (vehicle roof, wing etc.) the predominant polarization is vertical for all frequencies within the plane that includes the surface. Wideband polarization sub-band filtering [33] can also be applied to the transmitted signal to further improve LPI at the ENG receiver.

What is the expected improvement in Exclusion Zone and Protection Zone based ENG/TDL deconfliction?

As shown in Figure 34, every 6dB reduction in TDL interference level will result in a 2x reduction in EZ/PZ radius. An 18dB reduction in TDL interference to ENG receivers can be achieved with polarization processing. As a result, the EZ/PZ radius should be reduced by an additional factor of 8.

Conclusion:

Polarization is a fundamental property of the EM wave. It must be exploited for spectrum dominance and high probability of intercept when sensing in DSA systems.

PDL can be eliminated/mitigated to improve SNR and/or exploited to improve link SINR for anti-jamming and interference mitigation. PDL can be enhanced to reduce TDL signal levels in the ENG receiver, reducing the size of Exclusion Zones and Protected Zones by significant amounts.

PMD, when exploited in wide band systems, can greatly enhance interference mitigation and enable a host of spectrum sharing, DSA, signal classification and identification and cyber security methods.

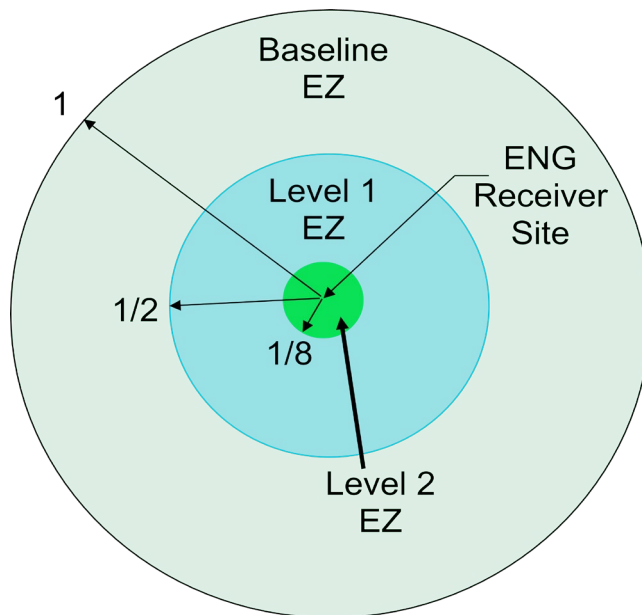


Figure 34: EZ/PZ Radius Improvements with 6dB and 18dB interference Reductions

7.2 Annex B: DRL Standard and Sharing Considerations

This section describes the original DRL-based sharing approach along with other consideration related to DRL-based spectrum sharing. The original DRL system was designed for ENG transceiver automatic transmitter power control (ATPC) applications. The standard was prepared by the Advanced Television Systems Committee (ATSC) Technology and Standards Group (TSG) [16]. It specifies the mechanisms necessary for basic identification and power control of

TV BAS transmitters, in either an automatic or a manual mode. ATPC is needed when adjacent channels are used and one transmitter is far from the ENG receiver and the other transmitter is near the ENG receiver, and sidebands from the near transmitter have the potential to jam the adjacent channel. In that case, ATPC enables the near transmitter to reduce its power level, thus, mitigating the sideband problem. There is no regulatory approval needed to implement the DRL sensing approach.

In the DRL standard, the DRL and ENG systems use separate antennas. DRL transmitters would be co-located with ENG receivers at elevated positions (e.g., towers). Multiple DRL transmitters and ENG receivers may share a tower or be in close proximity (e.g., at an antenna farm). DRL transmitters are located at least 10 ft. laterally from an ENG receiver to minimize out of band interference. In contrast to the approach presented in Section 5.1, it is also possible to develop a beaconing-based spectrum sharing approach where the DRL and ENG signals use separate antennas, however, additional analysis is needed to realize the cost and benefits of this approach.

DRL Signal Modulation

Another optional technical approach for spectrum sharing with ENG would be for the DoD radio to demodulate the DRL signal, which contains the ENG signal ID or perhaps the Signal to Noise Ratio (SNR)/link margin information. For example, if the ENG SNR is high, then interference criteria (Interference to Noise Ratio - INR) value can be increased, which would provide the DoD additional spectrum sharing opportunities without impacting the ENG operations. The DRL signal demodulation approach feasibility depends on the difficulty in continuously receiving the DRL signal and the latency of the DRL signal compared to the DoD system mobility. Additional analysis is needed to determine the cost and benefit of this approach.

ENG, DRL and TD-L Signal Polarization Considerations

ENG receivers are typically implemented with manually switched polarization diversity controlled by the studio engineer. The National Association of Broadcasters (NAB) handbook [17] recommends Circular Polarization, therefore, either RHCP or LHCP can be chosen at the receiver by the studio engineer to accommodate polarization reversals due to bounce (passive repeater) operations. The NAB handbook also recommends that the ENG transmitter include switched polarization capability to enhance adjacent channel rejection (ENG link to link interference suppression) when two or more links (i.e., 2 or more network affiliates) are operating in close proximity.

Sensing the DRL channel to verify ENG operations and then estimating the TD-L-to-ENG isolation based on signal strength, should take into account the added PDL between the DRL transmit antenna and the TD-L receiver, irrespective of whether DRL and ENG use the same antenna or separate antennas. For example, assume the DRL transmitter polarization is CP and the TD-L receiver is linear, an additional 3dB of measurement loss will need to be accounted for. Additionally, in case the DRL and ENG use separate antennas, care is needed to ensure that the DRL transmitter uses the same polarization as the ENG signal, otherwise this may introduce additional uncertainty in estimating the ENG signal.

More importantly, the DRL sensing technique is also susceptible to a large measurement error and resulting interference estimate error if a sidelobe measurement is confused for the main beam measurement of the DRL transmitter. This could result in 12dB or more measurement error. However, if the polarization of the DRL transmitter main beam is known, (via DRL message coding, data base hybrid approach below, machine learning etc.), then a polarization aware TD-L system can discriminate the sidelobes from the main beam [18] via a polarization measurement [19]. The sidelobes will exhibit unique polarization signatures as compared to the main beam.

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