

Using On-Shore Detected Radar Signal Power for Interference Protection of Off-Shore Radar Receivers

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report series

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ABBREVIATIONS AND SYMBOLS

BER	block error rate
BIT	Built-In Test
CBSD	Citizens Broadband Radio Service Device
ESC	environmental sensing capability
EMC	electromagnetic compatibility
FCC	Federal Communications Commission
ITS	Institute for Telecommunication Sciences
LTE	Long Term Evolution
NTIA	National Telecommunications and Information Administration
OSM	Office of Spectrum Management
PN	Public Notice
R&O	Report and Order
RF	radio frequency
SAS	spectrum access system

EXECUTIVE SUMMARY

In April 2015, the Federal Communications Commission (FCC) issued a Report and Order (R&O) in FCC Docket 12-354 [1] regarding future spectrum sharing between radar and non-radar systems in the band 3550–3650 MHz (called here the 3.5 GHz band); an FCC Public Notice (PN) [2] followed. The R&O and PN call for the establishment of an environmental sensing capability (ESC)¹ network of monitors working in concert with a Spectrum Access System (SAS) to protect offshore radar receivers from interference from the on-shore 3.5 GHz band terrestrial Citizens Broadband Radio Service Device (CBSD) communications network. There are currently two types of CBSDs: Category A and Category B. Category A CBSDs are lower in power, and limited to indoor or low-height outdoor operations. Category B CBSDs are higher power, and limited to outdoor operation. Category B CBSDs will only be authorized² for use after an ESC is approved and commercially deployed.

The radar receivers would be protected from interference by switching co-channel (or nearly co-channel) 3.5 GHz communications transmitters to other frequencies or even other bands at times and places where the terrestrial emissions might cause interference to the radars.

The need for ESC monitors and an associated SAS network controller to trigger actions for protection of offshore radar receivers begs the question of how the ESC/SAS would know that radars are present within potential interference zones of the terrestrial CBSD transmitters. (Assuming, per the conditions laid out in [2], that the radars will not provide the SAS with direct information that they are experiencing interference from CBSD devices.) One approach is to use a network of on-shore ESC monitors to sense signals coming from radar transmitters (co-located with radar receivers), and then infer, based on radar signal strength being received on-shore by ESC units, whether the radar receivers located off-shore may be receiving (or are about to receive) interference from the on-shore CBSDs that are in the vicinity of the ESCs.

This report shows a method to make that approach work. The key is to understand that the propagation losses from any radar transmitter to any given ESC monitoring station will be *equal to or less than* the propagation losses in the reverse direction—from terrestrial CBSD transmitters to the same radar receiver—provided that the ESCs are located near shorelines with sufficient antenna heights. With proper ESC station positioning (about 50 km apart), this report shows how such monitors will protect radar receivers from interference through the application of a simple SAS algorithm for local mitigation of interference from terrestrial CBSD transmitters. When radar and communication system technical characteristics are known, the entire monitoring approach can be reduced to a threshold test for the reception of transmitted radar signals relative to a known trigger-detection power level, $P_{triggers}$, at the ESC monitors (e.g., -64 dBm received radar peak power in a 1 MHz bandwidth). Each monitoring station then

¹ In the R&O definition, the ESC can be an entire *system* typically consisting of multiple sensor nodes that may have their own dedicated infrastructure network, or may use distributed CBSD-based sensing, or a combination of both. This report describes a specific infrastructure in which ESCs are considered to be synonymous with *individual* sensing agents or nodes that report to the SAS either directly or via some aggregating network.

² See 47 C.F.R. Section 96.15 and Section 96.67

produces a simple single-bit flag for threshold exceedance (or not) on a moment-to-moment basis, along with the frequency of incident radar signals. The SAS uses these flag-and-frequency outputs from the ESC network to mitigate interference to the radar receivers.

The approach described in this report will protect the radar receivers by making the SAS-controlled CBSD devices take mitigation action (e.g., possibly move channels) when necessary. This method ensures protection of the radars without feedback from the radar systems themselves. It achieves this objective with simplicity and robustness, and does so without any knowledge by the ESCs or the SAS of ship positions offshore.

Per Section 4, Summary and Conclusions, the authors recommend that:

- More detailed work should be performed on optimal ESC-to-ESC station spacing.
- CBSD transmitter base station aggregate-signal interference issues within radar beams as those beams sweep across littoral shores should be further examined.
- Laboratory tests and field demonstrations should be performed to validate this report's concept for ESC-SAS radar detection and radar receiver protection.
- The extent to which propagation reciprocity may not be fully satisfied in all areas needs to be studied, along with the extent to which $P_{trigger}$ levels might need to be adjusted downward to compensate for non-reciprocity in such areas.
- Although the exact levels of $P_{trigger}$ for deployment in aggregate-CBSD environments will be critically important for ESC implementation, such detailed analysis will need to be performed after CBSD deployments have actually been planned and built.
- Since failure of an ESC to detect and report a radar signal at $P_{trigger}$ would be a serious problem, as the SAS takes no mitigation action as long as an ESC reports no activity (a failed ESC not being known by the SAS to have a problem), consideration should be given to the incorporation of a built-in test (BIT) capability at each ESC. This capability would periodically calibrate ESC measured radar-signal power levels, and also verify periodically that each ESC detects and reports radar signals when they couple into the ESC antenna at or above the critical detection threshold power level.

This report presents technical description and observations on a particular proposal for ESC realization. It is not meant to imply preference for any ESC deployment model or suggest use of any preference for algorithms or thresholds by Industry. Also, in the R&O and PN definitions, ESCs are systems typically consisting of sensor nodes that may have their own dedicated infrastructure network, or may use distributed CBSD based sensing, or a combination of both. Since this paper only focuses on one specific realization of infrastructure type, similar analyses would be desirable to address other ESC models and infrastructure that differ from the description in this report.

USING ON-SHORE DETECTED RADAR SIGNAL POWER FOR INTERFERENCE PROTECTION OF OFF-SHORE RADAR RECEIVERS

Frank H. Sanders³, Edward F. Drocella,⁴ and Robert L. Sole⁴

A spectrum sharing scheme is considered in which ship-based radar stations are operating in the same spectrum band as on-shore communication transmitters, and in which the communication transmitters will cause interference to the radar receivers when interference, I , to noise, N , ratios in the radar receivers exceed a given level (e.g., $I/N \geq -6$ dB). The problem is that on-shore environmental sensing capability (ESC) monitors need to determine whether interference is occurring at off-shore radar receivers based only on information from the radar transmitters, with no information available from the victim radar receivers themselves. We describe an on-shore monitoring approach in which the principle of reciprocal propagation between the directions of radar-to-ESC and ESC-to-radar provides a simple go/no-go (single-bit) output from the ESCs to an associated Spectrum Access System (SAS) controlling the communication network, to perform on-shore channel changes for protection of the off-shore radar receivers. The ESC station outputs are based on a power-detection threshold, $P_{trigger}$, of radar signals at the ESCs (e.g., -64 dBm peak-detected power in 1 MHz bandwidth). Examples are provided in which ship-based radar receivers are protected by a simple algorithm applied to a group of on-shore ESCs and a SAS controller for the terrestrial communication network channel frequencies.

Keywords: antenna gain; Citizens Broadband Radio Service Devices (CBSDs); spectrum sharing; environmental sensing capability (ESC); interference monitoring; radar; radio propagation; spectrum access system (SAS); spectrum sharing

1. INTRODUCTION

In April 2015, the Federal Communications Commission (FCC) issued a Report and Order (R&O) in FCC Docket 12-354 [1], regarding future spectrum sharing between radars and non-radar systems, called Citizens Broadband Radio Service Devices (CBSDs), in the band 3550–3650 MHz (called here the 3.5 GHz band); an FCC Public Notice (PN) [2] followed. The R&O and PN call for the establishment of an environmental sensing capability (ESC) network of

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monitors⁵ working in concert with a Spectrum Access System (SAS) to protect offshore radar receivers from interference from the on-shore 3.5 GHz band terrestrial communications network. The radar receivers are to be protected from interference by SAS mitigation actions,⁶ the SAS mitigation itself being triggered by inputs from ESCs.

The need for ESC monitors triggering an associated SAS network controller for interference protection of off-shore, ship-based radar receivers begs the question of how the ESC-SAS might know that radars are present within potential interference zones of the terrestrial CBSD transmitters.

Per the conditions laid out in [2], no information will be available from the radars themselves regarding the extent to which their receivers are experiencing interference from outside sources. So the interference-mitigation system must work without feedback from the victim radar receivers.

This report shows a method based on radar signal strength being received by on-shore ESC stations. The key to this method is understanding that the propagation losses from any radar transmitter to any given ESC monitoring station will be *less than or equal to* the propagation losses in the reverse direction from terrestrial CBSD communication transmitters to the same radars' receivers. The scheme depends upon ESCs being located near shorelines, spaced about 50 km apart, with sufficient antenna heights to enable them to detect the radar signals from adequate distances.

When key radar and communication system technical characteristics are known, the entire monitoring approach can be reduced to a binary threshold test for the reception of transmitted radar signals relative to a known trigger-detection ESC power level, $P_{trigger}$ (e.g., -64 dBm⁷ received radar peak power in a 1 MHz bandwidth). ESCs are assumed to *not* have information about CBSD locations and deployment configurations. Instead, the approach described in this report expects the SAS to obtain channel occupancy flags from ESCs and then, based on built-in SAS knowledge of the CBSD network, take necessary actions with local CBSD transmitters to mitigate interference.

This proposed approach protects the radar receivers from interference without feedback from the radars and without identifying ships' positions. It achieves this objective with a robust, straightforward approach.

⁵ As noted in the Executive Summary, the R&O defines "ESC" as an entire *system* typically consisting of multiple sensor nodes that may have their own dedicated infrastructure network, or may use distributed CBSD-based sensing, or a combination of both. This report describes a specific infrastructure in which ESCs are considered to be synonymous with the *individual* sensing agents or nodes that report to the SAS either directly or via some aggregating network.

⁶ SAS interference mitigation is not specified in this report. It could consist of removing local co-channel (or nearly co-channel) CBSD transmitters from the radar frequency, but other mitigation strategies are possible. This report also does not address the important question of the total frequency range of CBSD channels for which mitigation action will be needed, relative to the radar operational frequency.

⁷ This is an example triggering power level; actual trigger power levels will probably differ from this value.

Note that this approach does not apply to ground-based mobile radars that are used within inland areas of operation or exclusion zone polygons as defined in [3]. A related approach may be possible for inland radar operations and zones, but is not a topic of this report.

ESC designs are not described in this report beyond the assumption that the stations will have antennas and receivers that are capable of detecting and discriminating radar signals in a CBSD-occupied environment. Nor are economic aspects of ESC station development, deployment, and operation considered. Likewise, the costs that may be associated with SAS interference-mitigation actions for CBSDs are not considered. This report only describes technical aspects of the authors' proposed strategy for ESC radar signal detection and related ESC alerts to the associated SAS.

1.1 Engineering Background: 3.5 GHz Band Electromagnetic Compatibility Studies

As part of ongoing spectrum sharing studies for this band, NTIA's Office of Spectrum Management (OSM) has studied electromagnetic compatibility (EMC) characteristics of both incumbent and yet-to-be-developed government systems in the 3.5 GHz band and has developed coastal exclusion zones that are expected to eventually become sharing zones [3]. Government systems in the band include, but are not limited to, ship-based naval radars. Additionally, NTIA's Institute for Telecommunication Sciences (ITS) and OSM have published reports addressing measurement results for radar-to-LTE interference effects and thresholds [4], [5], LTE-to-radar interference effects and thresholds [6], and incumbent radar emission characteristics [7]; LTE base station and handset signals were used in the studies because future 3.5 GHz band terrestrial networks will most likely predominantly utilize some version of LTE technology. Another report examined in detail the emission characteristics of a 3.5 GHz LTE wireless local area network (WLAN) wireless access point (WAP), or hotspot [8]. (All emission measurements in these NTIA Technical Reports were performed in adherence to the best-practices criteria provided in [9].)

A significant result of studies [4], [5], and [6] is that, when LTE radios and Radar 1 units (Radar 1 being a 3.5 GHz naval radar described in [6] and [7]) share frequency channels, the radar receivers can be expected to experience interference effects before the CBSD receivers do.⁸ That is, radar receiver performance in the presence of CBSD signals is the limiting factor in channel-sharing between the systems. Radar receivers off-shore are expected to experience harmful interference from CBSD transmitters tens of decibels ([6]) before CBSD receivers suffer degradation in their data throughput or increases in their block error rates (BERs). Note that high-power effects to the ESC or CBSD receivers from the radar transmitter are not discussed in this report; it is an important topic in [1] that NTIA is addressing in another test program.

⁸ Note that 3.5 GHz CBSDs have yet to be built or deployed; NTIA studies have used LTE systems as technical stand-ins for CBSDs. Additional technical studies may be undertaken when 3.5 GHz CBSDs become available, if they are not LTE-based.

As shown in [6], the threshold for obscured⁹ targets in Radar 1 receivers in the presence of interference from LTE signals is at an interference power level, I , that is 6 dB below the internal thermal noise, N , of the radar receiver: $I/N = -6$ dB is the interference threshold in the Radar 1 receiver.

Using best available digital terrain elevation data (DTED), propagation models and extensive Monte Carlo-based digital computer simulations, NTIA has performed an extensive study to determine the coastal exclusion zones [3]. These are areas where it would be expected that the aggregate power of CBSD transmitters would exceed the protection criteria (obscured-target interference) in off-shore Radar 1 receivers [7]. These calculated zones typically extend a few tens of kilometers inland.

At this time, 3.5 GHz CBSD devices will not be allowed to operate within these zones. But after future deployment of 3.5 GHz ESC and SAS, CBSD devices will be allowed within these zones; the CBSDs will use ESC and SAS to avoid interference with radar operations.

The sharing picture is complicated by current lack of knowledge of the eventual on-shore CBSD deployment characteristics and the uncertainty of propagation characteristics in the CBSD band in a variety of environments (e.g., urban, suburban, and rural). For example, while the FCC rules specify *maximum* EIRPs, and studies (i.e., [3]) have been performed using certain assumptions for CBSD transmitter EIRPs and spatial lay-down densities, *actual* CBSD transmitter power levels and deployment densities may be significantly lower than the limits set in these rules and studies. In view of these uncertainties, complications and possible differences between preliminary assumptions for band-sharing conditions versus eventual real-world deployments, monitoring of actual radar signals in the 3.5 GHz band will provide a practical and effective way forward for eventual spectrum sharing within the zones described in [3]. Such a monitoring approach is proposed herein.

1.2 Proposed ESC-SAS Monitoring and Control Approach

This report proposes an approach in which the characteristics of the radar transmitters, radar receivers and CBSD transmitters are used in concert with an assumption of reciprocal propagation (ship-to-shore and shore-to-ship) to allow ESCs to raise single-bit logic flags when some incident radar signal power threshold is exceeded. This is a power threshold at which communication system signals running in the opposite direction (shore-to-ship) would exceed a critical (e.g., $I/N = -6$ dB) interference protection threshold in the radar receivers. When ESCs raise these logic flags and send the sensed radar frequencies to the SAS, the SAS will effect mitigation actions for nearby co-channel (or nearly co-channel) CBSD transmitters. To ensure radar protection, all co-channel CBSD transmitters located in sharing zones between affected ESCs will be switched, along with CBSD transmitters out to distances of half-way to the nearest-to-adjacent untriggered ESCs. Within these triggered ESC zones, SAS-activated interference

⁹ The Radar 1 receiver does not have constant false alarm rate (CFAR) processing. In the presence of interference its targets are obscured by false alarms, manifested as bright strobes on the radar screen display. The false-alarm obscuration makes the targets invisible to the radar's operators.

mitigation will be invoked along the entire width of the identified coastal sharing zones as identified in [3] or some updated version of it.

As will be shown below, this approach has the advantage of simplicity and robustness at the expense of forcing somewhat more on-shore transmitter mitigations than are absolutely necessary. This approach has the advantage of protecting the off-shore radar receivers without any feedback information from those receivers to the SAS.

The ESCs should be spaced along the coast at station-to-station distances that are practical (i.e., on the order of a few tens of kilometers); they should be located with radio frequency (RF) line-of-sight coverage from one to the next along the shore, running as close as possible to the shoreline.

The method proposed in this report also has the advantage of not identifying the positions of the radars. The received power levels at the triggered ESCs will *not* be transmitted to the SAS in this scheme; the SAS will only obtain single-bit threshold-exceeded flags and sensed radar frequencies from the ESCs. This is a minimal approach to ESC operation *vis-à-vis* the off-shore radar operations; there is no way to transmit *less* than a single bit of information from an ESC plus a sensed frequency for the SAS to act upon. If the ESCs cannot transmit this much information, then an ESC-based approach for triggering SAS mitigation action would be logically precluded.¹⁰

¹⁰ Knowledge of the logic flags from triggered ESCs would allow a third party only to realize that a ship was somewhere off-shore along a long segment of coastline at an unknown ship-to-shore distance with no fix for the ship's latitude and longitude. And even that information could be derived only if the third party knew *where* the triggered ESCs were located. ESC locations might be masked by assigning arbitrary, randomly generated identification codes to ESC stations (e.g., via dynamically assigned (DHCP) Internet Protocol addresses), the SAS itself being the only entity where ESC identifiers are correlated with ESC physical locations.

2. RECIPROCAL-PROPAGATION MONITORING APPROACH

2.1 Basic Geometry

Figure 1 shows the basic geometry of the reciprocal-propagation monitoring approach.

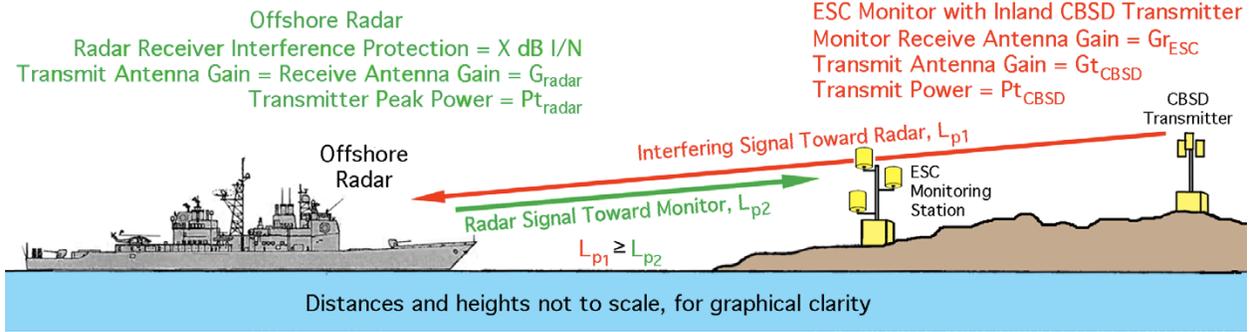


Figure 1. Basic geometry of the reciprocal-propagation monitoring approach.

2.2 Power-Trigger ($P_{trigger}$) Threshold Equation Derivation

When a radar is off-shore from a network of ESC monitors and associated terrestrial communication transmitters, the power from the CBSD transmitters that is coupled into the radar receiver will be (in decibel units):

$$Prx_{radar} = Pt_{CBSD} + B_{radar/CBSD} + Gt_{CBSD} + Li_{CBSD} - L_{p1} + Gr_{radar}$$

where:

Prx_{radar} = power from terrestrial CBSD transmitter coupled into the radar receiver;

Pt_{CBSD} = power output from the CBSD transmitter;

$B_{radar/CBSD} = 10\log(B_{radar_rx}/B_{CBSD_tx})$ if $B_{radar_rx} < B_{CBSD_tx}$; otherwise $B_{radar/CBSD} = 0$ dB;

B_{radar_rx} = radar receiver noise equivalent bandwidth;

B_{CBSD_tx} = bandwidth of transmitted CBSD signal;

Gt_{CBSD} = effective gain of the CBSD transmitter antenna toward the radar;

Li_{CBSD} = insertion loss within the CBSD transmitter system, written as a gain term (e.g., -2 dB);

L_{p1} = propagation loss, written as a positive term, from CBSD transmitter to radar receiver;

Gr_{radar} = effective gain of the radar antenna toward the CBSD transmitter.

The power received from the radar transmitter at the ESC monitoring station will be:

$$Prx_{ESC} = Pt_{radar} + B_{ESC/radar} + L_{i_radar} + Gt_{radar} - L_{p2} + Gr_{ESC}$$

where:

Prx_{ESC} = power from the radar transmitter received in the ESC monitor;

Pt_{radar} = peak power output from the radar transmitter;

$B_{ESC/radar} = 10\log(B_{ESC}/B_{radar_tx})$ if $B_{ESC} < B_{radar_tx}$; otherwise $B_{ESC/radar} = 0$ dB;

B_{ESC} = ESC receiver noise equivalent bandwidth;

B_{radar_tx} = bandwidth of transmitted radar signal;

L_{i_radar} = insertion loss within the radar transmitter system, written as a gain term (e.g., -2 dB);

Gt_{radar} = effective gain of the radar antenna toward the ESC monitor;

L_{p2} = propagation loss, written as a positive term, from the radar transmitter to the ESC monitor;

Gr_{ESC} = effective gain of the ESC monitor antenna toward the radar transmitter.

The interference-avoidance criterion is:

$$I_A = Pt_{CBSD} + B_{radar/CBSD} + L_{i_CBSD} + Gt_{CBSD} - L_{p1} + Gr_{radar}$$

where:

I_A = allowed power level (e.g., $I_A = -117$ dBm (see below)) for interference avoidance in the radar receiver. Subscript A refers to the corresponding maximum allowed I/N level ($A = -6$ dB for Radar 1).

Re-arranging these equations as functions of the propagation factors L_{p1} and L_{p2} , we have:

$$L_{p1} = -I_A + Pt_{CBSD} + B_{radar/CBSD} + L_{i_CBSD} + Gt_{CBSD} + Gr_{radar}$$

$$L_{p2} = -Prx_{ESC} + Pt_{radar} + B_{ESC/radar} + L_{i_radar} + Gt_{radar} + Gr_{ESC}$$

In order to provide assurance that the radar receivers are protected from the on-shore transmitters, the propagation loss from ship to ESC needs to be *equal to or less than* the propagation loss between the terrestrial transmitters and the ship's radar receiver. That is, we need:

$$L_{p1} \geq L_{p2}$$

This condition will always be met so long as the ESC stations are located at least as close to the shoreline as any of the communication transmitter stations, with appropriate antenna heights (Figure 1).

Writing out the individual terms for $L_{p1} \geq L_{p2}$:

$$-I_A + Pt_{CBSD} + B_{radar/CBSD} + L_{i_{CBSD}} + Gt_{CBSD} + Gr_{radar} \geq -Prx_{ESC} + Pt_{radar} + B_{ESC/radar} + L_{i_{radar}} + Gt_{radar} + Gr_{ESC}$$

Note that the radar antenna gain does not appear in this equation; this is because the radar transmits and receives on the same antenna with $Gt_{radar} = Gr_{radar}$. The terms subtract out with only the radar transmitter power, bandwidth, noise figure and I/N affecting $P_{trigger}$. The symmetry between the antenna gain terms applies equally to the radar's backlobes and sidelobes; backlobe and sidelobe coupling therefore does not need to be considered.

Solving for the power received by the monitoring station, and setting the radar transmitter antenna gain equal to the radar receiver antenna gain (same radar antenna being used in both directions), which causes the radar antenna gain to drop out of the equation:

$$Prx_{ESC} \geq I_A - Pt_{CBSD} - B_{radar/CBSD} - L_{i_{CBSD}} - Gt_{CBSD} + Pt_{radar} + B_{ESC/radar} + L_{i_{radar}} + Gr_{ESC}$$

Finally, we solve for the interference avoidance criterion I_X in terms of the radar receiver characteristics:

$$I_X = 10 \log(kTB_{radar_{rx}}) + 10 \log(nf) + A = N_{BW_{radar_{rx}}} + NF + A$$

where:

k = Boltzmann's constant, 1.38×10^{-23} J/K·Hz;

T = receiver ambient temperature, K;

$B_{radar_{rx}}$ = radar receiver noise equivalent bandwidth, Hz;

nf = radar receiver noise factor, linear;

A = allowed interference level relative to radar receiver noise floor, e.g., -6 dB;

$N_{BW_{radar_{rx}}}$ = radar receiver noise power at temperature, T , in bandwidth $B_{radar_{rx}}$;

NF = radar receiver noise figure, dB;

So, with the critical received ESC power level for SAS triggering being $P_{trigger}$,

$$P_{trigger} \geq N_{BW_{radar_{rx}}} + NF + A - Pt_{CBSD} - B_{radar/CBSD} - L_{i_{CBSD}} - Gt_{CBSD} + Pt_{radar} + B_{ESC/radar} + L_{i_{radar}} + Gr_{ESC}$$

This is the power-trigger threshold equation for ESC receivers. If the terms for CBSD transmitter power and antenna gain are joined into a single term for CBSD effective isotropic radiated power ($EIRP_{CBSD}$)¹¹, then the equation can be written as:

$$P_{trigger} \geq N_{BW_radar_rx} + NF + A - EIRP_{CBSD} - B_{radar/CBSD} - L_{i_CBSD} + Pt_{radar} + B_{ESC/radar} + L_{i_radar} + Gr_{ESC}$$

2.3 Example Calculation of $P_{trigger}$

Consider, for example, $P_{trigger}$ for a CBSD transmitter running at maximum allowed EIRP¹² in a coastal sharing zone with the following parameter values:

$$T = 290 \text{ K};$$

$$B_{radar_tx} = 1/(1 \text{ } \mu\text{s pulse width}) = 1 \text{ MHz};$$

$$B_{radar_rx} = 1 \text{ MHz};$$

$$10\log(kTB) = -174 \text{ dBm/Hz} + 60 \text{ dB/MHz} = -114 \text{ dBm/MHz}$$

$$NF_{radar} = 3 \text{ dB};$$

$$A = -6 \text{ dB}$$

$$EIRP_{CBSD_max} = (Pt_{CBSD} + Gt_{CBSD})_{max} = +47 \text{ dBm/10 MHz};$$

$$B_{CBSD} = 10 \text{ MHz};$$

$$B_{radar/CBSD} = 10\log(1 \text{ MHz}/10 \text{ MHz}) = -10 \text{ dB};$$

$$B_{ESC} = 1 \text{ MHz};$$

$$B_{ESC/radar} = 10\log(1 \text{ MHz}/1 \text{ MHz}) = 0 \text{ dB};$$

$$L_{i_CBSD} = -2 \text{ dB};$$

$$Gt_{CBSD} = 6 \text{ dBi};$$

$$Pt_{radar} = 1 \text{ MW in } 1 \text{ MHz} = +90 \text{ dBm in } 1 \text{ MHz};$$

$$L_{i_radar} = -2 \text{ dB};$$

¹¹ With the CBSD transmitter insertion loss, L_{i_CBSD} , still kept as an explicit term.

¹² The CBSD maximum effective isotropic radiated power ($EIRP_{CBSD_max}$) is taken from available FCC documents [1] and [2]. The radar characteristics are those of Radar 1. Insertion losses for both systems are taken as -2 dB.

$Gr_{ESC} = 0$ dBi.

Then $P_{trigger}$ is:

$$P_{trigger} \geq -114 \frac{dBm}{MHz} + 3 dB - 6 dB - 47 dBm + 10 dB + 2 dB + 90 dBm/MHz - 2 dB + 0 dBi$$

which sums to

$$P_{trigger} \geq -64 dBm/MHz$$

This is the spectrum power density that would be used to trigger a radar detection flag from an ESC with 0 dBi antenna gain to its associated SAS. This calculation is provided only to show how $P_{trigger}$ can be computed; actual $P_{trigger}$ levels for ESCs will probably *not* be -64 dBm/MHz.

It is critically important that $P_{trigger}$ be computed in the bandwidth of the victim radar receiver, in this example 1 MHz. It will not generally be adequate to simply use total transmitter power levels for CBSDs and radars. Rather, these transmitted power levels need to be converted to equivalent spectrum power densities in the bandwidths of victim radar receivers. Note, too, the linear functional dependence of $P_{trigger}$ on $EIRP_{CBSD_max}$: For every decibel that a limit on $EIRP_{CBSD_max}$ might ever be increased, $P_{trigger}$ will be reduced by a corresponding decibel.

2.4 Calculated $P_{trigger}$ Levels for Additional 3.5 GHz Radars

Only Radar 1 currently operates on U.S. ships in the 3.5 GHz sharing band. New models of shipborne radars may operate in this band in the future. Table 1 shows example calculated $P_{trigger}$ levels for a parametrically distributed set of possible characteristics for such radars, along with existing Radar 1. The radar parameters in Table 1 are not predictions for future radar characteristics in the band; rather, they range parametrically over possible future radar designs, distributed for characteristics of pulse width, chirp¹³ width and transmitter power.

In Table 1, CBSD EIRP is held constant at +47 dBm/10 MHz for comparative purposes. For all cases it is assumed that $Gr_{ESC} = 0$ dBi and that the I/N threshold, X , for CBSD interference in each radar receiver will be -6 dB. The ESC receiver bandwidth is held at 1 MHz for the example calculation, but could be varied in actual ESC designs.¹⁴ Radar noise figure and insertion loss factors are held constant at 3 dB and 2 dB, respectively.

In Table 1, $P_{trigger}$ levels vary from -64 dBm/MHz to -90 dBm/MHz for ESC receivers (as already noted, with 0 dBi antenna gain). When new types of radars eventually operate in the 3.5 GHz band, ESC stations might need to discriminate $P_{trigger}$ based on received radar signal

¹³ Chirping is frequency modulation during pulses; the chirp bandwidth is B_c and the pulse width is τ . Advanced solid-state transmitter radars often use chirped modulation as a pulse compression technique to compensate for the lower power levels that solid state transmitters generate relative to higher-powered tube-type transmitters.

¹⁴ High-speed digitizer-based ESCs could sample in wider bandwidths and then down-sample to narrower bandwidths tailored to individual radar parameters in the band.

parameters (e.g., pulse width and pulse repetition rate). Alternatively, ESC stations might utilize a generalized radar-detection algorithm that does not distinguish among radar types, with $P_{trigger}$ set to the lowest value across radar types. Based on Table 1, this would be -90 dBm/MHz with 0 dBi ESC antenna gain.

Table 1. $P_{trigger}$ Across a Parametric Range of Possible Future 3.5 GHz Radar Characteristics.

Radars	P_{radar} (dBm)	B_{radar_tx} (MHz)	B_{radar_rx} (MHz)	$P_{trigger}$ (dBm/MHz)
Radars 1 (existing)	+90	1	$1/\tau = 1$ MHz	-64
High power P0N¹⁵ Short (0.1 μs) pulse	+90	10	$1/\tau = 10$ MHz	-74
High power P0N Long (10 μs) pulse	+90	0.1	$1/\tau = 0.1$ MHz	-64
Low power Q3N¹⁶ Narrowband Chirped $B_c = 3$ MHz $\tau = 100$ μ s	+74	$B_c = 3$ MHz	$B_c = 3$ MHz	-85
Low power Q3N Wideband Chirped $B_c = 10$ MHz $\tau = 4$ μ s	+74	$B_c = 10$ MHz	$B_c = 10$ MHz	-90

2.5 Computing a Lower Limit for ESC $P_{trigger}$ Sensing

ESC receivers will have a lower power limit at which they can detect and therefore trigger on radar signals. This limit will be determined by the ESC receiver bandwidth, noise figure, peak-detection functionality, external noise from local CBSD transmitters, and minimum signal-to-noise ratio required for reliable radar signal detection; the limit will be the sum of these terms:

$$P_{ESC_trigger_limit} = 10 \log(kTB_{ESC}) + P_{peak_detector} + NF_{ESC} + N_{external} + SNR_{min}$$

where:

kTB_{ESC} = ESC receiver thermal noise at temperature T in bandwidth B_{ESC} , watts;

$P_{peak_detector}$ = peak detector noise relative to root mean square (RMS) thermal noise, dB;

NF_{ESC} = noise figure of the ESC receiver, dB;

$N_{external}$ = external noise level in the ESC receiver bandwidth, dB;

¹⁵ P0N is the modulation-code designation for amplitude-modulated (carrier wave, or CW) pulses.

¹⁶ Q3N is the modulation-code designation for frequency-modulated (chirped) pulses.

SNR_{min} = minimum required signal-to-noise ratio for reliable radar signal detection, dB.

For example, suppose the following parameter values:

$$T = 290 \text{ K};$$

$$B_{ESC} = 1 \text{ MHz},$$

$$P_{peak_detector} = 10 \text{ dB};$$

$NF_{ESC} = 4 \text{ dB}$, consistent with the performance of commercially available low-noise amplifiers;

$$N_{external} = 6 \text{ dB/MHz}^{17};$$

$$SNR_{min} = 10 \text{ dB}.$$

In this case, the ESC lower-bound trigger limit is $P_{ESC_trigger_limit} = -84 \text{ dBm/MHz}$; this would be a lower limit for $P_{trigger}$ for any given radar type. This limit is 20 dB below the value of $P_{trigger}$ that we calculate for Radar 1.

This limit is 6 dB above the theoretical limit of -90 dBm/MHz that might need to be met for the hypothetical future wideband-chirped radar of . If such a radar were ever to be deployed, the ESC antenna gain could be upgraded to, say, 10 dBi for protection of the radar, increasing the $P_{trigger}$ threshold level in the ESC receiver to -80 dBm in that case.

2.6 Aggregate-CBSD $P_{trigger}$ Consideration

For expositional simplicity, the example $P_{trigger}$ levels presented in this report have been calculated for a single CBSD transmitter at a high EIRP (+47 dBm) interfering with a radar receiver at any single moment in time. It is likely however that ($N > 1$) co-channel CBSD transmitter stations will occur within any single wedge of radar beam coverage. In that case, $P_{trigger}$ will need to be adjusted for the expected number, N , of CBSDs and their associated EIRPs for aggregation of their cumulative power within the radar's main beam. A power-summation technique similar to that implemented in [3] can be used for $N > 1$ CBSDs in the radar beam.

Although this adjusted calculation of $P_{trigger}$ for multiple CBSDs will be critically important for ESC implementation, such detailed analysis will need to be performed after CBSD deployments have actually been planned and built. $P_{trigger}$ values will therefore be expected to vary along segments of coastline depending on the exact characteristics of actual CBSD deployments.

¹⁷ This value has been picked only for this computational example; the actual value of $N_{external}$ will have to be assessed when actual CBSD transmitter networks are deployed.

2.7 Additional Margin for $P_{trigger}$

Cases may occur in which analysis shows that lower propagation losses are expected between radars and CBSDs on high ridgelines overlooking the ocean as compared to propagation losses between radars and shoreline-located ESCs; spatial differences in ESC and CBSD locations could cast doubt on the assumptions made herein regarding reciprocal propagation losses. In one case, for example, an ESC might be too high to couple into a surface duct while much lower CBSDs do couple into the duct. Or, there could be inversion layers in one path and not the other. Under some conditions, higher terrain farther inland (i.e. the U.S. west coast) may provide a more advantageous location for the ESC than at water's edge. And, the Radar 1 antenna beam has a $1/\csc^2$ vertical cross section that puts more power at higher elevation angles than at the lowest elevation angles. The topic of possible conditions under which propagation reciprocity might not fully hold is so broad that it needs to be fully addressed in future studies and tests.

However, the approach proposed in this report can still be made to work even under the condition that full reciprocity does not exist in both propagation directions. The way to make it work is to assess the extent to which propagation in two directions is expected to *not* be reciprocal in both directions, and then to adjust the level of $P_{trigger}$ downward enough to compensate for the expected propagation differential. For example, if the propagation coupling to some mountaintop location inland from an ESC were expected to be 10 dB stronger than to ESCs located on the nearby shoreline, then $P_{trigger}$ would be adjusted downward by a corresponding amount of 10 dB.

2.8 Possible ESC Antenna Height Diversity

To accommodate propagation path variations, including those that might cause propagation reciprocity to not fully hold, some ESC stations in areas prone to this condition may need to employ some antenna height diversity. This idea is sketched schematically in the picture of the ESC in Figure 1. Some ESC antenna height diversity, especially using higher antenna heights where shorelines rise rapidly from the ocean as on the west coast and Hawaii, may be helpful in improving the probability that ESC triggers adequately protect off-shore radar receivers in such areas. As with the topic of propagation reciprocity in general, this idea will need to be examined in more detail in future studies and tests.

3. ESC-SAS TRIGGER-AND-CONTROL STRATEGY

3.1 ESC Monitoring Station Shoreline Spacing

As described above, and depicted schematically in Figure 1, this approach depends on the condition that $|L_{p1}| \geq |L_{p2}|$. To achieve this, the ESC monitoring stations typically need to be positioned as far forward toward shorelines as possible, so as to keep CBSD base station transmitters as far or further from the off-shore radars. This requirement is also, as shown here, a driving force in the selection of optimal shoreline spacing between ESC monitoring stations.

In the following scenario, a CBSD base station transmitter is located about as close to the shoreline as the ESC stations, sitting halfway between them as shown in Figure 2. The CBSD location has about 1 dB *less* propagation loss to the radar than either of the adjacent ESCs, assuming comparable antenna heights and free-space propagation.

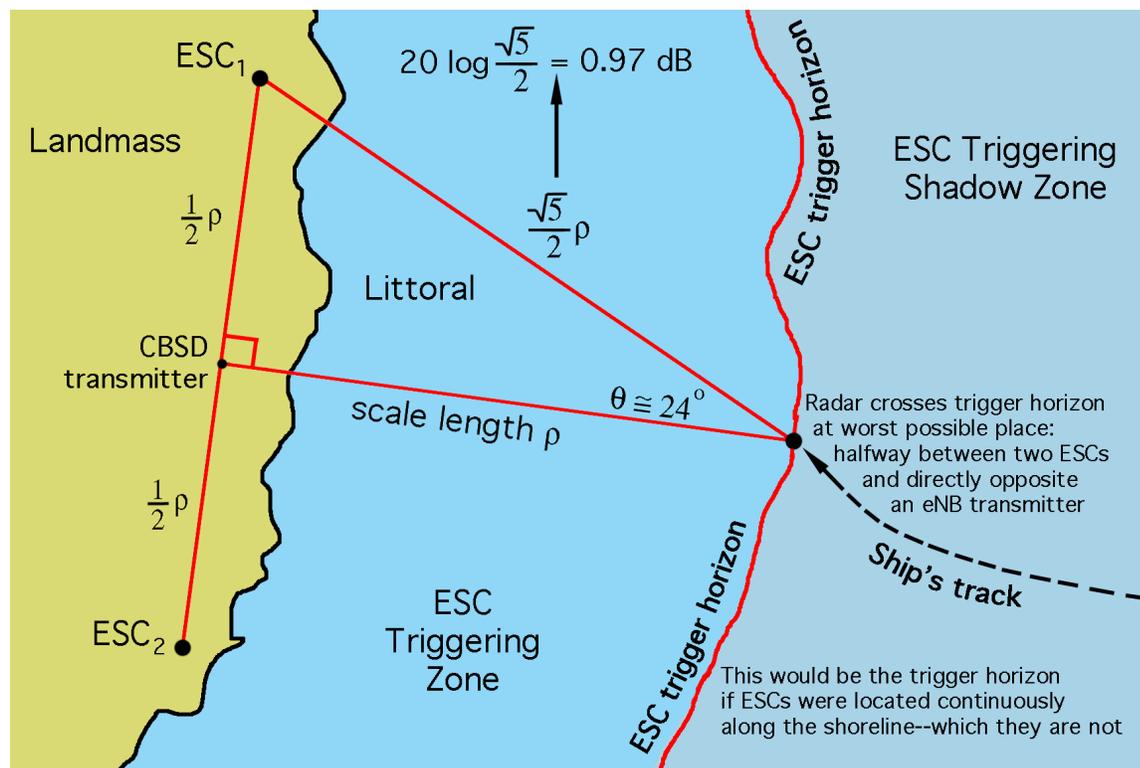


Figure 2. Optimal ESC shoreline spacing = ρ , driven by the possibility of a CBSD base station transmitter sitting on the shore halfway between two ESCs.

Referring to Figure 2, an off-shore radar is initially located in the “triggering shadow zone”, but situated too far over the radio horizon to trigger either of the ESCs. But the ship carrying the radar eventually moves to a position off-shore where it is at a worst-case location for ESC detection relative to an interfering CBSD base station transmitter. This is the place where the radar *would* have triggered an ESC *if an ESC had been directly across the water from it*, but there is instead an interfering, co-channel CBSD transmitter. The two nearest ESCs are further from the radar, at some distance on either side of the CBSD base station transmitter.

In this case, the ESCs would not have detected the radar (the incident radar signal having not yet reached the critical $P_{trigger}$ threshold at their positions) even though the CBSD base station transmitter would be producing radar interference at or above allowable level.

This might seem to be a problem, but this problem’s solution is the key to understanding an approach for optimally spacing the ESCs along the shoreline. Recognizing that the only way to completely eliminate this problem would be to position an infinite number of ESCs along shorelines, which is obviously not possible or practical, the question is “How can ESCs be positioned so that the largest possible difference, $\Delta_{propagation}$, in the propagation path loss between the radar and the ESCs versus the radar and a near-shore CBSD base station transmitter between two ESCs does not exceed some given amount? That is, is there a way to assure that the propagation differential between them to be, say, $\Delta_{propagation} < 1$ dB?”

The answer is yes, and Figure 2 shows the solution. Assuming that the CBSD base station transmitter and the two ESCs have comparable antenna heights and that propagation is free space ($1/r^2$) $\Rightarrow 20\log(r)$ between all points, then the difference in propagation on the two critical paths (the baseline leg and the hypotenuse of the right triangle) is $(5/4)^{0.5} = 1.118$. Then $\Delta_{propagation} = 20\log(1.118) = 0.96$ dB. *This condition holds if the distance to the triggering horizon from the ESCs, ρ , is the same as the ESC-to-ESC spacing on the shore.*

With this spacing of ρ between the ESCs, the ESC triggering levels can simply be adjusted downward by the amount of $\Delta_{propagation} \approx 1$ dB, that is downward from $P_{trigger}$ to $(P_{trigger} - 1$ dB), to ensure protection of the off-shore radar receiver under this condition; the 1 dB downward shift in $P_{trigger}$ will ensure that, even under this condition, the ESC-SAS network will protect the off-shore radars, no matter where they cross the triggering horizon.

Note that the ESC-to-ESC distance separation criterion does *not* depend on radar characteristics. This is significant because new types of radars may be introduced into the 3.5 GHz band in the future. It would be potentially problematic if ESC stations needed to be re-spaced when new radars came onto the scene, but the non-dependence of ESC-to-ESC spacing on radar characteristics means the future introduction of new radars into the band will not be an issue in this regard.

3.2 Estimating ESC-to-ESC Spacing

As shown in Figure 2, ρ (the distance from the ESCs at which off-shore radar signals will exceed the triggering threshold) is a linear scaling factor. How large will ρ be? For Radar 1, running at 1 GW EIRP (+120 dBm) or more, the distance at which their signals drop below $P_{trigger}$ is never achieved as a result of $1/r^2$ propagation or anything close to it. Rather, it is the place where the radar antenna drops below the earth’s horizon as seen from the ESC and CBSD base station antennas; this condition is depicted schematically in Figure 3. The *radio horizon* of these antennas marks the place where the free-space, $1/r^2$ over-water propagation factor (approximately) transitions to a much faster, exponentially dependent distance-loss factor, where

diffraction begins to occur. Note that this methodology does not include ducting,¹⁸ but should still protect the radar receiver when it occurs since ducting expands the RF radio horizon.

So, ρ is about equal to D_{LOS} in Figure 3. For a smooth round Earth of radius r_{Earth} , the geometric line-of-sight distance, d_{LOS} , visible from a height, h , above ground level (AGL) is derived in [10]:¹⁹

$$d_{LOS} = \sqrt{2hr_{Earth}}$$

For h in meters and d_{LOS} in kilometers, this equation reduces to:

$$d_{LOS} = 3.57 \cdot \sqrt{h}$$

For example, if the radar antenna height, h_{ship} , were 45 m AGL and the ESC antenna height, h_{ESC} , were 30 m AGL, then $D_{LOS} = (d_{LOS-ship} + d_{LOS-ESC}) = (24 \text{ km} + 20 \text{ km}) = 44 \text{ km}$.

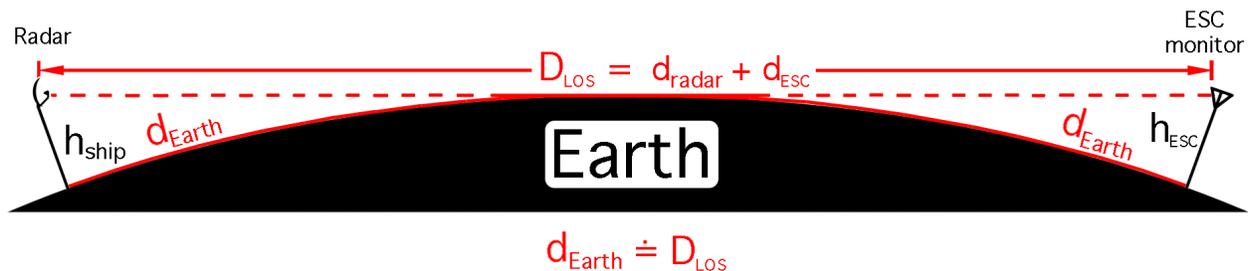


Figure 3. ESC-to-ESC geometry for antenna height h AGL at limit of line-of-sight coverage between stations. Earth's curvature is exaggerated for graphical clarity.

If $4/3$ earth's radius is used to calculate the horizon distances instead of the earth's physical radius, consistent with the physics of radio-horizon diffraction-zone behavior, then the radio horizon distance is increased by a factor of $(4/3)^{0.5} = 1.15$, and the nominal 44 km radar trigger-horizon distance goes to just over 50 km. *Here $\rho = 50 \text{ km}$, but this is used only as a working (albeit realistic) example; more work needs to be done to refine this distance.*

3.3 Minimum ESC Distance from CBSD Base Station Transmitters

How close to a CBSD base station transmitter could an ESC receiver be located, with the ESC still able to detect radar signals that are co-channel to the CBSD? Unless special signal-processing protocols are implemented, an ESC needs to be able to detect a radar signal at a level of $P_{trigger}$ in the presence of co-channel CBSD transmissions based on some sort of minimum

¹⁸ Greatly simplified, ducting is weather-related anomalous propagation in which radio waves are trapped within an atmospheric layer between the earth's surface and the top of a temperature inversion; the waves dissipate over distance at *less* than the ordinary free-space ($1/r^2$) spherical-front expansion rate.

¹⁹ The corresponding map distance measured along the surface of the earth, d_{Earth} , is slightly longer than d_{LOS} , but the two lengths are virtually identical at runs on the order of tens of kilometers.

amount of radar signal power above the received CBSD signal power. The need for radar signal detection at $P_{trigger}$ or above, with $P_{trigger}$ itself being somewhat in excess of local co-channel CBSD signals, means that ESC stations cannot be co-located with CBSD base station transmitters.

The minimum free-space separation distance may be computed via the following equation:

$$20 \log(D_{ESC_to_CBSD_min}) = EIRP_{CBSD} + B_{ESC/CBSD} - 32.5 - 20 \log(f) - (P_{trigger} - \Delta_{detect})$$

or:

$$D_{ESC_to_CBSD_min} = 10^{(EIRP_{CBSD} + B_{ESC/CBSD} - 32.5 - 20 \log(f) - (P_{trigger} - \Delta_{detect})) / 20}$$

where:

$D_{ESC_to_CBSD}$ = minimum free-space ESC-to-CBSD separation distance, km;

$EIRP_{CBSD}$ = EIRP power of CBSD transmitter in the direction of the ESC station, dBm;

$B_{ESC/CBSD} = 10 \log(B_{ESC}/B_{CBSD_tx})$ if $B_{ESC} < B_{CBSD_tx}$; otherwise $B_{ESC/CBSD_tx} = 0$;

f = CBSD transmitter frequency, MHz;

-32.5 dB = proportionality constant for frequencies in MHz, power in dBm and distances in km;

Δ_{detect} = amount that peak power of radar pulses must exceed the CBSD transmitter power in the ESC receiver, dB.

Consider, for example, the following case:

$EIRP_{CBSD} = +47$ dBm;

$B_{ESC/CBSD} = 10 \log(1 \text{ MHz}/10 \text{ MHz}) = -10$ dB;

$f = 3600$ MHz;

$P_{trigger} = -64$ dBm;

$\Delta_{detect} = 3$ dB.

Then the minimum ESC-to-CBSD free-space separation distance is 1.0 km.

This calculation is performed under the assumption that the ESC antenna is omnidirectional, so that the ESC antenna gain toward the radar signal is the same as toward the CBSD; that calculation can be modified as the ESC antenna gain varies with direction.

Table 2 shows example results for a variety of CBSD EIRP levels paired with ESC detection-threshold levels that were calculated above in Table 1.

Table 2. Examples of Minimum Free-Space ESC-to-CBSD Separations for $\Delta_{detect} = 3$ dB.

CBSD Total EIRP in 10 MHz (dBm)	CBSD EIRP Density (dBm/MHz)	$P_{trigger}$ (dBm/MHz)	$P_{trigger} - 3$ dB (dBm/MHz)	Minimum Free-Space Distance Separation (km)
+47	+37	-64	-67	1.0
+47	+37	-74	-77	3.3
+47	+37	-85	-88	12
+47	+37	-90	-93	21
+37	+27	-64	-67	0.33
+37	+27	-74	-77	1.0
+37	+27	-85	-88	3.7
+37	+27	-90	-93	6.6
+27	+17	-64	-67	0.10
+27	+17	-74	-77	0.33
+27	+17	-85	-88	1.2
+27	+17	-90	-93	2.1

3.4 Detection Problem for Possible Future Low-Observable Radars in the Presence of Co-Channel CBSB Base Station Transmitter Emissions

As gathered from inspection of the equation for $D_{ESC_to_CBSB}$ and of the results shown in Table 2, separations increase with higher CBSB transmitter power levels and lower radar-detection ESC thresholds. When the CBSB EIRP is +47 dBm and the radar is relatively difficult to detect at $P_{trigger} = -90$ dBm (fourth line in Table 2), for example, the computed separation distance grows to 21 km. The parameters in Tables

and 2 represent mostly theoretical cases for future radar development. But radars with similar parameters to those shown in Tables

and 2 *do* presently operate in other bands; it is not inconceivable that similar radars could someday be developed for 3.5 GHz.

This raises the question of what the limits may be for detection of possible future low-observable radars by ESCs in the presence of self-interference from co-channel CBSB signals. Not only can ESC-to-CBSD separation distances grow to tens of kilometers, as indicated in Table 2, but for low-observable radars an additional problem would arise.

This would be the amount of external noise that *aggregates* of CBSB transmitters could generate in the sharing band. This external, aggregate CBSB transmitter noise level will increase the effective noise level in the ESC receivers by some amount, *no matter where the ESC receivers are located*. This constant background noise will add linearly to whatever amount of power each ESC is receiving from its nearest-neighbor CBSB transmitter(s). If an ESC is close enough to a CBSB that the power from the individual CBSB substantially exceeds the background noise, then the separation equation results (e.g., the results of Table 2) may still be applied.

But if an ESC is so far from an individual CBSD that the CBSD power approaches the background noise level, then background noise level will begin to dominate as the limiting factor in the ESC receiver's capability to detect radar signals. If, for example, $\Delta_{detect} = 3$ dB (the value used in Table 2), then this limiting case will occur when the sum of the individual CBSD power and the background noise represents an increase of $\Delta_{detect} = 3$ dB in the overall amount of noise in the ESC receiver. A 3 dB increase will, of course, represent the case in which the background noise level equals the noise from the nearest individual CBSD transmitter.

Consider an ESC with a 4 dB noise figure which is peak-detecting radar signals in a 1 MHz bandwidth. The ESC receiver's internal-only noise level, $P_{ESC_internal_noise_floor}$, will be:

$$P_{ESC_internal_noise_floor} = 10\log(kTB_{ESC}) + NF_{ESC} + N_{detector_relative_to_RMS}$$

where:

$$B_{ESC} = 1 \text{ MHz};$$

$$NF_{ESC} = 4 \text{ dB};$$

$$N_{detector_relative_to_RMS} = +10 \text{ dB for peak detection.}$$

The internal noise of the ESC receiver would be $-114 \text{ dBm} + 4 \text{ dB} + 10 \text{ dB} = -100 \text{ dBm}$ in this case. This is 7 dB below the -93 dBm value of $(P_{trigger} - \Delta_{detect})$ in Table 2 that was used for a theoretical future low-observable radar with $P_{trigger} = -90 \text{ dBm}$ (Table 1).

Based on this result, if the external noise, $N_{external}$, generated across the sharing band by a CBSD aggregate were to approach something like 6 or 7 dB of total increase above internally generated thermal peak-detected noise in ESC receivers, it could become difficult for *any* ESC system (not just the particular ESC system approach that is described in this report) to detect future types of relatively low-observable radar signals even when the ESC receivers are situated far enough from individual CBSDs to meet the criterion of the separation equation.

3.5 Additional Considerations for ESC Detection of Low-Observable Radars

As noted above, low-observable radar signals can be difficult due to transmission of low peak power spread across wide chirped-frequency ranges. Additionally, low-observable radar technology can also include random or pseudo-random frequency hopping across wide frequency ranges and very limited beam-dwell periods in any single direction in space. These features can result in a very limited number of pulses being directed toward any shore-based ESC on any given frequency at any moment in time. It is therefore conceivable that some future 3.5 GHz radars might be developed that might be very difficult to detect by ESCs; low observable radars could present a problem for detection by *any* ESC-based band-sharing scheme, not just the proposal in this report. Technical interchange may therefore be needed between future radar designers and ESC engineering groups.

3.6 Effects of Possible Future Radar Designs on ESC Detection in General

Future radar designs at 3.5 GHz could present some more challenges. If such radars were to eventually frequency-hop or chirp across the entire sharing band, they could conceivably block the entire band in a given area by triggering all ESCs on all available CBSD channels in the band.

Another challenge for ESCs in the future could be changes in 3.5 GHz radar waveforms that are not fully understood by ESC designers. ESCs themselves might need to be remote-programmable (e.g., as field-programmable gate array-based digitization systems) to change their detection functionality as future radar designs evolve in this band.

We note these possible future considerations as a generalized technical comment for *all* possible ESC-based detection schemes for future spectrum management of the 3.5 GHz band. These considerations for the future will not be particular to the approach proposed in this report.

3.7 Consideration of Other Conditions and Geometries

The case considered so far in this report is for the ESC-to-ESC spacing as shown in Figure 2, where a ship continuously operating its radar transitions across the local (nearly) line-of-sight horizon at distance ρ between itself and ESCs. There are two other cases that bear consideration. These are (1) ducting of the radar signal from distances *well beyond* ρ , and (2) the radar being turned off until the ship is *well within* ρ , and then being turned on without warning when it is just a few kilometers from shore. Since both of these conditions can be expected to eventually occur at any given shoreline location given shipboard radar operations, this scheme needs to be checked to verify that it still works under such conditions.

Ducting conditions are analyzed as follows: The worst-case condition is still when the radar is located on the same perpendicular to the ESC-to-ESC baseline as shown in Figure 2, but ducting causes the radar signal to exceed $P_{trigger}$ when the ship is much further away than ρ . In this case, the angle θ in Figure 2 becomes *smaller* than the nominal value of 24 angular degrees on Figure 2 and the difference between the triangle's leg and hypotenuse becomes smaller than the nominal ratio of $(5/4)^{0.5} = 1.118$. Thus the delta propagation factor ($A_{propagation}$) decreases under ducting propagation conditions and the scheme works just as well under those conditions.²⁰

For the second case, where the radar turns on abruptly when it is closer (possibly much closer) to shore than ρ , the radar is well within the radio horizons of all nearby ESCs when it begins to transmit and the radar signal will instantly exceed the critical threshold at the CBSD base station transmitter *and* the two adjacent ESCs of Figure 2.²¹ Since all nearby ESCs are triggered, the ESC-SAS network will activate to protect the radar along that entire segment of coastline,

²⁰ As noted in Section 2.7, $P_{trigger}$ can be adjusted downward when more sensitivity to the radar signals is required.

²¹ In fact, the important technical issue in this case could be that the radar signal might overload or even damage nearby ESC and CBSD receivers. NTIA will address that topic in another report.

including the CBSD base station transmitter located between two ESCs. Just as for the ducting conditions, the system works as well under this condition as it does for the geometry of Figure 2.

3.8 Number of ESC Stations Needed for Total Shoreline Coverage

This scheme does not need monitoring stations at inland locations. Indeed, inland deployment is contra-indicated by the need to have the smallest possible propagation loss between the ESCs and the off-shore radars.²² With a station-to-station spacing on the order of 50 km and an estimated distance of 2800 km along the U.S. east coast from northern Maine to southern Florida, this spacing would require about 56 east coast ESC stations. The Gulf coast (about 2100 km) would require around 42 ESCs and the west coast (also 2100 km) another 42. A total of fewer than 150 ESCs would be needed to cover the totality of all three U.S. coastlines.

3.9 The ESC-SAS Transmitter Control Algorithm

Figure 4 shows the concept for the ESC-SAS transmitter-control algorithm; we describe the algorithm here. Consider a group of ESC stations labeled A–F, as shown in Figure 3. The algorithm works as follows:

- All ESCs (such as A–F in Figure 3) continually monitor the shared spectrum band for radar signals within a broad range of characteristics (such as pulse width, pulse repetition rate and beam-scanning interval).

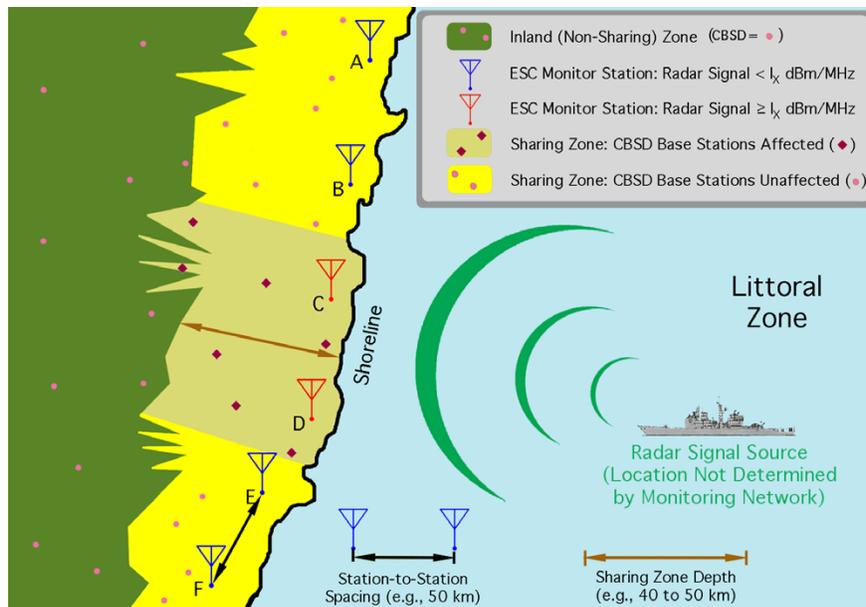


Figure 4. Concept for the ESC-SAS transmitter-control algorithm with six ESC stations A–F.

²² Some additional ESCs may be needed at a limited number of inland port facilities and waterways.

- ESCs send status updates to the SAS at whatever rate the ESCs can scan the shared spectrum. As long as the ESCs see no radar signals above $P_{trigger}$, they periodically send “nothing seen” bits (say, zeroes) to the SAS.
- Eventually a radar signal appears in the shared band. This signal might gradually increase in power from background noise levels and becomes detectable by the ESC as it reaches the coast from a distant ship somewhere over the horizon via tropospheric scattering or ducting. Or it might appear suddenly, at high incident power, when a ship within line-of-sight of the shore (e.g., within 10 kilometers of the shoreline) turns on its radar.
- The ESCs where radar peak power exceeds $P_{trigger}$ now set their radar trigger-bit flags to “1” and register the frequency (or frequencies) of the locally occurring radar signal(s); they send this information to the SAS. In Figure 4, these are stations *C* and *D*.
- The SAS registers the ESCs that are triggering on radar signals. The SAS activates interference mitigation for CBSD transmitters that are co-channel (or nearly co-channel) with the radar frequency if those transmitters:
 - are located between any two triggered ESCs (*C* and *D* in Figure 4) or
 - are located up to half-way between any triggered and non-triggered ESCs (up to half-way between pairs *B–C* and *D–E* in Figure 4).²³
- The ESCs continue to monitor the radar signal presence. The *status quo* of local CBSD transmitter interference mitigation is maintained until radar signals no longer trigger the ESCs. When the coast is (literally) clear and the ESC trigger-bit flags re-set to zeroes, the on-shore CBSD transmitters may be allowed by the SAS to resume their pre-mitigation operation.
- The algorithm cycles back to its baseline (no radar signal present) mode, with the ESC-SAS systems waiting for others radars to appear.

In Figure 4, for example, all CBSD transmitters are mitigated by the SAS if they are co-channel (or nearly co-channel) to the radar and are located between stations *C* and *D*. Within these triggered zones, the SAS mitigates CBSD transmitters all the way from the coast to the inland edge of the exclusion zone. By including not just CBSD transmitters between pairs of triggered ESCs (e.g., *C* and *D* in Figure 4) but also up to half-way between the triggered and non-triggered ESCs on each end of the string of stations (as shown in Figure 4), assurance is provided that no on-shore CBSD transmitters in the sharing zone will cause interference to the off-shore radars.

3.10 ESC End-of-Chain Effects

The algorithm has been described here as if the ESC stations form an endless chain. But every such chain must have an end. There may also be cases in which a single ESC covers an area. In these cases, the algorithm works as follows:

²³ The half-way criterion is driven by the 1-dB maximum radar power offset half-way between the stations, as shown in Figure 3.

For the end of a series of ESC stations, all CBSD transmitters located at or beyond the last (final) triggered ESC in the line will be mitigated. The mitigation will continue up the chain as far as the half-way point between the last triggered ESC and the first non-triggered ESC. For areas covered by a single ESC, all CBSD transmitters in the ESC coverage area will be mitigated when their associated ESC is triggered.

3.11 Conservatism of the Algorithm

Under this algorithm, CBSD transmitters in sharing zones that are co-channel or nearly co-channel with off-shore radars will be mitigated if they are located between pairs of triggered ESCs and also if they are up to half-way between pairs of triggered and non-triggered ESCs. This means that the SAS is likely to command *more* CBSD transmitters to perform mitigation than absolutely need to be affected; this approach is conservative in its protection of off-shore radar receivers.

Conservatism in interference protection is an important consideration in a band-sharing scenario where the protection must be performed blindly, when the radar receivers are not providing any feedback to the SAS as to whether they are experiencing interference or not. Without a significant degree of inherent, built-in conservatism, it is difficult to see how to achieve and maintain confidence that the radar receivers are not experiencing interference when the ships are in littoral waters.

3.12 Possible Future Development of the Algorithm

It is conceivable that, at some time subsequent to the deployment of an ESC-SAS network using the algorithm described here, the SAS options for CBSD interference mitigation might be refined. For example, it is possible that the SAS could incorporate detailed CBSD location information, real-time transmitter power levels, antenna gains, and antenna directional sectors to better define the exact CBSD transmitters that need to be mitigated when ESC radar flags are raised.

If the ESCs themselves were to eventually transmit received radar-signal power levels instead of merely the binary-state trigger flags, it might be possible for the CBSD mitigation to be further fine-tuned for exact distances of CBSDs from shore, in addition to the refinements available from using the CBSD parameters mentioned above. In other words, the algorithm described here can conceivably be expanded in the future to allow a less conservative approach to mitigating CBSD transmitter interference to off-shore radars.

3.13 Non-Derivation of Radars' Position Information

The FCC rules have a requirement that 3.5 GHz band-sharing ESC monitors must not “store, retain, transmit, or disclose operational information on the movement or position of any federal system” [2]. The ESC-SAS approach proposed herein meets this requirement by transmitting a minimal amount of information (threshold-detection flag plus frequency) from ESCs to the SAS.

In order to use the ESC outputs to even roughly locate ships off-shore, it would be necessary to know *both* the locations of the ESCs themselves *and* the incident radar peak power levels that each ESC is sensing. If the ESCs use identifiers that are randomly assigned without regard for ESC locations, as proposed, which are correlated with geographical locations only in a SAS-internal look-up table, a SAS service provider that obtains the ESC trigger flags will be unable to correlate those flags with identifiable geographical zones and ship locations.

Furthermore, the *non-transmission* of detected radar power levels from each ESC means that *no* information is sent from ESC units to the SAS that could be used to infer (even roughly) the directions of radars relative to pairs of ESCs by comparing received power levels from one ESC to the next. No information is available that would allow a third party to know, for example, based on hypothetically equal power levels received at two adjacent ESCs, that a radar might be located somewhere on or near a line that runs perpendicular to the baseline connecting the two ESCs.

3.14 Built-In Test Capability for ESCs

Because the baseline state of ESCs is null-state flags, the SAS will not know if an ESC develops some sort of fault causing non-detection of radar signals, or if an ESC receiver becomes uncalibrated and therefore is not reporting correctly relative to $P_{trigger}$. To provide *positive verification* of proper ESC performance, it may be desirable to consider the incorporation of a built-in test (BIT) capability at each ESC. The BITs would periodically calibrate and verify ESC receiver performance. With each ESC reporting the results of periodic BIT runs, network operators would have assurance that the ESCs are in fact reporting any radar signals that actually occur at or above $P_{trigger}$.

4. SUMMARY AND CONCLUSIONS

4.1 Summary

Lack of knowledge of the eventual on-shore 3.5 GHz CBSD deployment characteristics and the uncertainty of propagation characteristics in that band in a variety of environments (e.g., urban, suburban and rural) are factors to be considered in spectrum sharing at 3.5 GHz. FCC rules specify *maximum* EIRPs, and studies such as [3] have used assumptions for CBSD transmitter EIRPs and spatial lay-down densities. But *actual* CBSD transmitter power levels and deployment densities may be less than the allowed maximums. Monitoring of actual radar signals in the 3.5 GHz band will provide a practical and effective way forward for eventual spectrum sharing within littoral sharing zones. The approach is made simpler and more robust by taking advantage of reciprocal propagation characteristics between ship-to-shore and shore-to-ship radio paths.

This report describes such a monitoring approach. It describes an ESC-SAS approach for radar monitoring and associated interference-mitigation action in which a network of shore-based ESC monitoring stations inform their associated SAS whenever an incident peak radar power signal exceeds a critical threshold value at each of their locations. The approach contains the following features:

- A string of coastal ESC monitoring stations is established wherever 3.5 GHz band-sharing terrestrial communication networks have been deployed near U.S. shorelines.
- The ESC stations are positioned so that their near-shore locations and antenna heights make their propagation losses toward off-shore radars *less than or equal to* the propagation losses between off-shore radars and any terrestrial 3.5 GHz transmitter base stations that are positioned inland from the ESCs. The ESC-to-ESC spacing should be about the same as the trigger-detection horizon distance, likely on the order of 50 km.
- The ESCs continually monitor the shared band for signals from radars that could experience interference from the communications network CBSDs.
- Whenever a pre-set radar peak power detection threshold is exceeded in an ESC monitor, it transmits to the SAS: (1) a single-bit flag, and (2) the frequency of the radar signal. The detection threshold is a function of the known characteristics of the radar transmitters and receivers, and of the on-shore CBSD transmitters. ESCs are given random, non-sequential identifiers; only the SAS can correlate ESC identifiers with geographical locations.
- The SAS assesses, moment-by-moment, the status of all ESC monitoring stations in any given coastal spectrum-sharing zone. Some necessary ESC distances from CBSD base stations, needed to ensure reliable radar detection in the presence of co-channel communication signals, are shown in Table 2 for various conditions.
- For co-channel (or nearly co-channel) CBSD base station transmitters located between pairs of triggered ESCs, and up to half-way between nearest-adjacent triggered and non-triggered

ESCs, the SAS takes interference-mitigating action to protect the radar receiver from CBSD interference.

- Each CBSD transmitter station is maintained in mitigated (non-interference) status by the SAS until the ESCs are no longer triggered by radar signals.
- This ESC-SAS algorithmic cycle is maintained as long as the 3.5 GHz terrestrial communication network operates in any given coastal sharing zone.

4.2 Features of This Approach

This approach has the following features:

- It is robustly simple.
- It requires no propagation predictions, assumptions, or calculations.
- It works under a wide variety of propagation conditions.
- It performs no radar position (ship position) determinations.
- It works with a small number of ESC stations (probably less than 150 ESCs for all three U.S. coasts), if the spacing is about 50 km from one ESC station to the next.
- It works with no feedback from radar receivers to the SAS as to their state of interference; it eliminates guesswork and uncertainty from the ESC-SAS radar-protection solution.
- The algorithm can be modified in the future to allow a less conservative approach to mitigating CBSD transmitter interference to off-shore radars.
- It can accommodate future radar development at 3.5 GHz.

4.3 Recommendations for Future Work

The authors recommend that further work be performed on:

- More detailed determination of the distance-scaling term ρ , as this variable is essentially the same as the optimal ESC-to-ESC station spacing.
- Examination of terrestrial CBSD transmitter base station aggregate-signal interference issues within radar beams as those beams sweep across littoral areas, with possible resulting adjustment of $P_{trigger}$ thresholds.
- Laboratory tests and field demonstrations to validate this report's concept for ESC-SAS radar detection and radar-receiver protection.

- Additional work on the extent to which propagation reciprocity may not be fully satisfied in all areas, and the extent to which $P_{trigger}$ levels may need to be adjusted downward to compensate for non-reciprocity under such conditions.
- *Although the exact levels of $P_{trigger}$ for deployment in aggregate-CBSD environments will be critically important for ESC implementation, such detailed analysis will need to be performed after CBSD deployments have actually been planned and built.* Tests and measurements may be needed to verify the analysis results.
- The provision of a built-in test (BIT) capability at each ESC to periodically calibrate ESC measured radar-signal power levels and also to periodically verify that each ESC is detecting and reporting radar signals at or above $P_{trigger}$. A BIT capability is needed because while failure of an ESC to detect and report a radar signal at $P_{trigger}$ would cripple the entire approach, the SAS would not know that an ESC had become non-responsive (or had developed mis-calibrated received radar power levels) in the absence of periodic BIT reports (or something equivalent) from each ESC.

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