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## **Systems Approach to Ground Vehicle Electromagnetic Compatibility**

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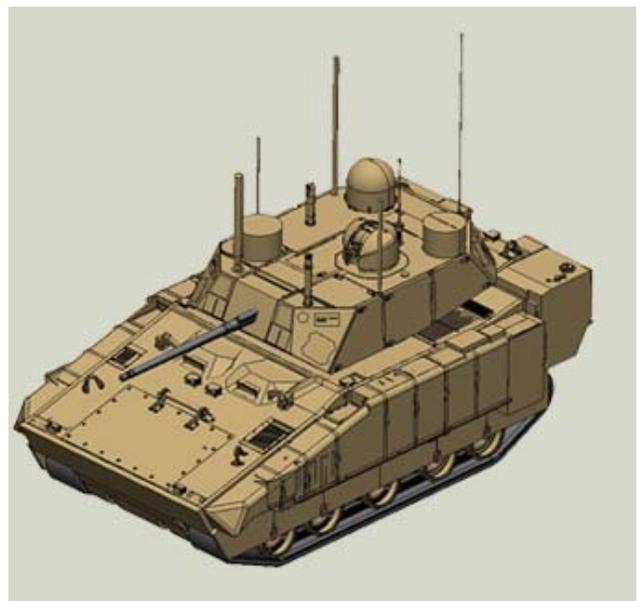
### **ABSTRACT**

BAE Systems has developed a system level approach for identifying the issues associated with collocating Blue Force Communications with other on-board emitters. Specific scenarios include broadband interference caused by Electronic Warfare (EW) and radio congestion. Our approach is divided into three (3) functional areas to resolve this complex situation: (1) the proper selection and placement of Advanced Antenna Structures. (2) Receiver front end overloading protection through the use of a Wide Band Frequency Domain Cancellation Analog/Digital RF cancellation process. (3) The further refinement of the signal through the use of Digital Signal Processing for interference estimation, tracking, and cancellation based on efficient adaptive algorithms.

### **INTRODUCTION**

Ground Vehicle Topside RF integration continues to grow in complexity as more sensors, communication channels and self-protection systems are required for today's war fighting. To aggravate the situation, vehicles in very close proximity to each other cause additional mutual self-interference.

This paper describes a methodology for mitigating RF interference through the use of system engineering practices directed at reducing coupling effects, understanding the interference sources and using processing to improve performance.



Although some solutions are suggested, it is not the intent of this paper to define solutions but to suggest a course of action to describe and understand ground vehicle interference (cosite).

## **(1) PROPER ANTENNA SELECTION AND PLACEMENT**

The first stage of resolving the complex issues associated with collocating Blue Force Communications with other on-board emitters is through the use of various antennas; ranging from Multi-Band Antennas (MBA) to distributed Armor Embedded Antennas (AEA). These antennas can provide omni-directional coverage, sectorized coverage or when phase properly can create far field nulls which aids in low probability of detection and jamming. This section will discuss the system approach associated with the implementation of antennas on ground vehicles.

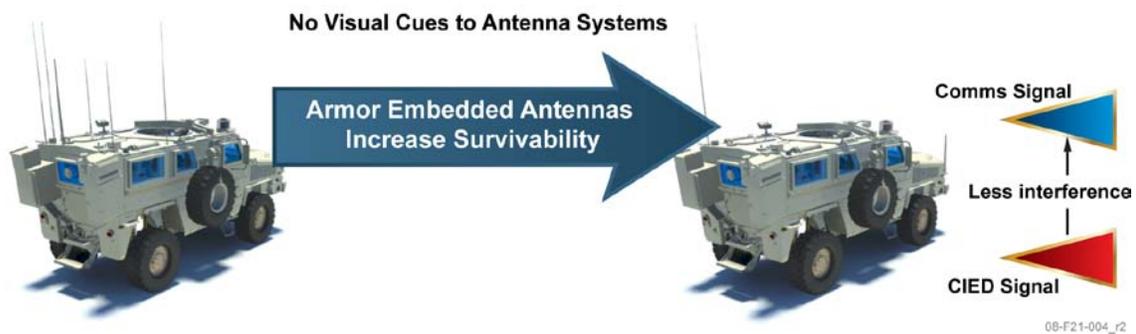
The key to a total antenna system that is used for communications, electronic warfare and signal intelligence is to maintain adequate isolation between each function so the systems do not interfere with each other.

Through the use of Electromagnetic (EM) modeling and simulation installed antenna performance can be predicted. In a typical scenario antennas are installed on a platform and the far field radiation patterns are predicted. To determine the near field antenna to antenna coupling is much more complicated than modeling of the far field. For this reason physical measurement of the antenna to antenna coupling is also performed to get accurate data. This data is used in the total system analysis to predict system performance prior to fielding of the system. Various antenna types can assist in increasing the isolation between functions. For omni-directional coverage Multi-Band Antennas (MBA) are ideally suited and when coupled with sectorized or directional antennas such as Armor Embedded Antennas (AEA) multiple function within the same band of operation can exist simultaneously.

With today's modern ground vehicles the "real estate" to install antennas is limited. By utilizing MBA's that support more than a single frequency band of operation, the number of antennas can be minimized. Today's MBA's are capable of covering from VHF to S-Band (27-6,000 MHz) in a single antenna structure. These antennas have been implemented on the Brigade Combat Team Modernization (BCTM) program with great success. Some key performance parameters of MBA's are: Improved isolation between CREW and Communications, Improved Field of View (FOV) over existing systems, reduced visual signature and Improved Frequency Coverage. These MBA's provide the omni-directional coverage that is required for most communication waveforms; such as SINGARS, EPLRS, WNW, SRW, HAVEQUICK and JTIDS.

MBA's when couple with AEA's, provide optimal system performance. The need for an armor embedded or conformal antenna solution comes from the desire to

have antennas with a low signature (Radar Cross Section - RCS and visual) so the antennas do not distinguish the platforms function. Additionally, by installing antennas on the side of a platform the isolation between functions can be increased which mitigates the cosite issues with multiple functions within the same band of operation. The cosite between communications and counter IED is a major issue today. Current counter IED systems produce cosite interference by inadvertently jamming own-vehicle communications. Placing armor embedded antennas on the sides of the vehicles helps isolate the counter IED transmissions from communications antennas resulting in reduced cosite interference. An armor embedded antenna solution supports a directional or distributed jamming capability and enhances the platform survivability. Having these antenna embedded into the armor provides an optimal balance between system performance and survivability.

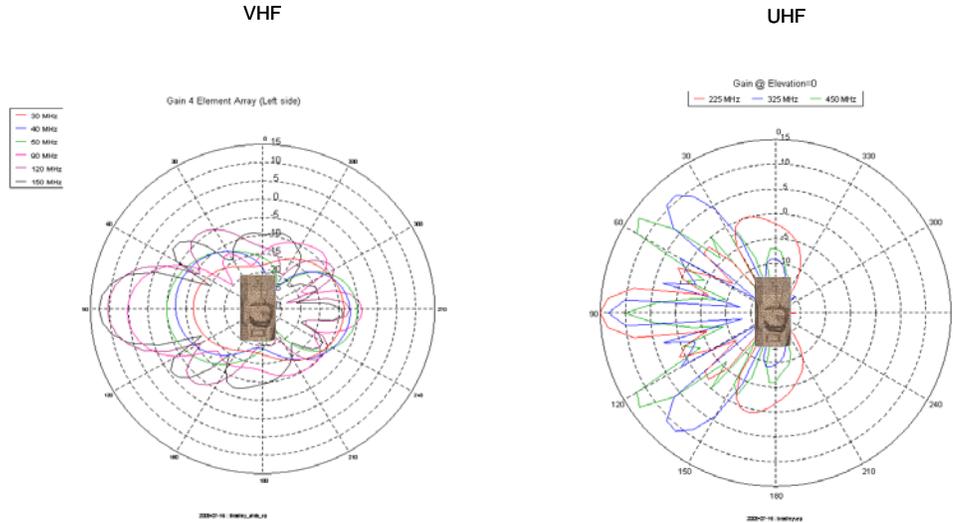


**Figure 1: Armor Embedded Antenna Benefits**

The applications for an armor embedded antenna solution can cover any directional system requirement. Direction Finding Emitter Mapping Systems, directional Jamming Systems, Combat Identification Systems and directional Communications Systems all can be implemented in armor embedded systems. The key factors that make armor embedded antennas attractive are similar to the structural embedded antennas implemented on aircraft. The size and weight impacts to the platform can be minimized and the signature (both visual and RCS) can be reduced. By having the armor encompass both the armor and antenna functions, the antenna system survivability is increased while minimizing the weight impact. Another clear benefit is that prime real estate, which is currently not utilized for antenna integration, can be taken advantage of with the embedding of the antennas in the armor.

The exact implementation of armor embedded antenna is platform specific just as it is on aircraft. Through electromagnetic modeling and testing, the solution that provides the best compromise between all the key performance parameters can be reached. By having armor embedded antennas and antennas such as MBA's (whip type), the tools are in place to provide the platforms with the optimal configuration to meet the performance requirements.

BAE Systems' approach to covering from VHF to UHF (30-450 MHz) entails populating the vehicle with several armor embedded panels and feeding to obtain the desired pattern. The trade space includes how to phase the antennas to obtain the best pattern within the real estate on the platform and the antenna performance.

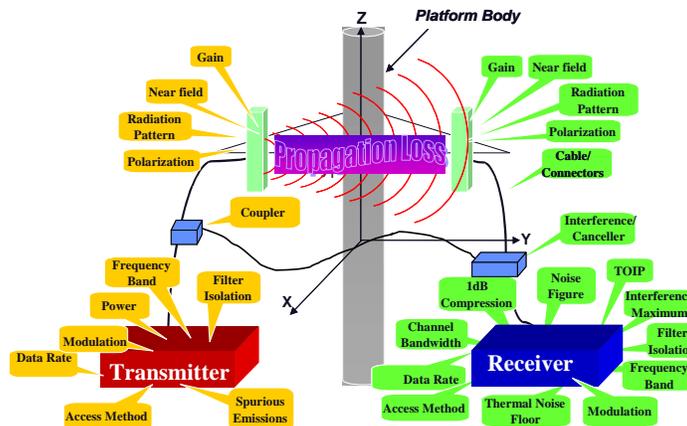


**Figure 2: Directional Broadside Radiation Pattern**

The initial modeling shows that a directional pattern is formed by arraying multiple AEA's as shown in Figure 2.

**(2) RECEIVER FRONT END OVERLOADING PROTECTION**

Receiver front end overloading, which is referred to as Cosite interference occurs when the reception of a desired signal is degraded due to one or more platform transmitters radiating at the same time. The principle co-site characteristics typically studied are shown below in Figure 3 .



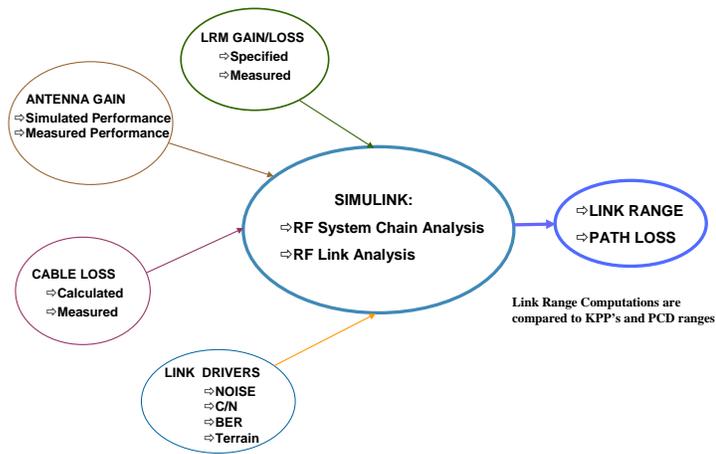
**Figure 3: RF Characteristics used in cosite study**

The key sources of platform Cosite interference are:

- **Transmitter Power Level**
  - Tx Carrier Power causes Gain Compression and Desensitization in Receivers, ahead of any Filtering
  - Automatic Gain Control (AGC) Capture
- **Wideband Thermal Noise Floor**
  - Transmitter Noise is a Broadband Additive Noise Jammer over a wide Frequency Range
- **Transmitter Spurious**
  - Unintentional Modulation of Carrier by Leakage Signals such as Clock Harmonics, Synthesizer Reference Harmonics, Switch Closures and Openings, Digital Noise appearing at Discrete Frequencies
- **Back Intermodulation**
  - Special Case where High Power Signals impinge on the output of another Power Amplifier - It may cause the PA to go non-linear - When this happens, IM products will be generated
- **Rusty Bolt**
  - Interference can be generated in the Environment when 2 or more High Level Signals impinge on any object which cause Nonlinear Interactions of the Signals

## **Understanding the Problem**

A properly developed Cosite interference analysis model accounts for all interference effects, including transmitter spectral power, reciprocal mixing, cross-modulation, Inter-modulation Distortion (IMD), transmit noise and receiver desensitization as well as second order effects caused by the platform itself. The model provides characterization of interference between communications, radar and sensor source/victim pairs. All communications and non-communications links are identified, including emitters and receivers, the signal format (waveform) and propagation medium. The location of the platform antennas and the coupling (or isolation) is also incorporated. Finally, understanding how the communication links and sensors is used in an operational scenario is determined along with the Link quality needed for each signal format.

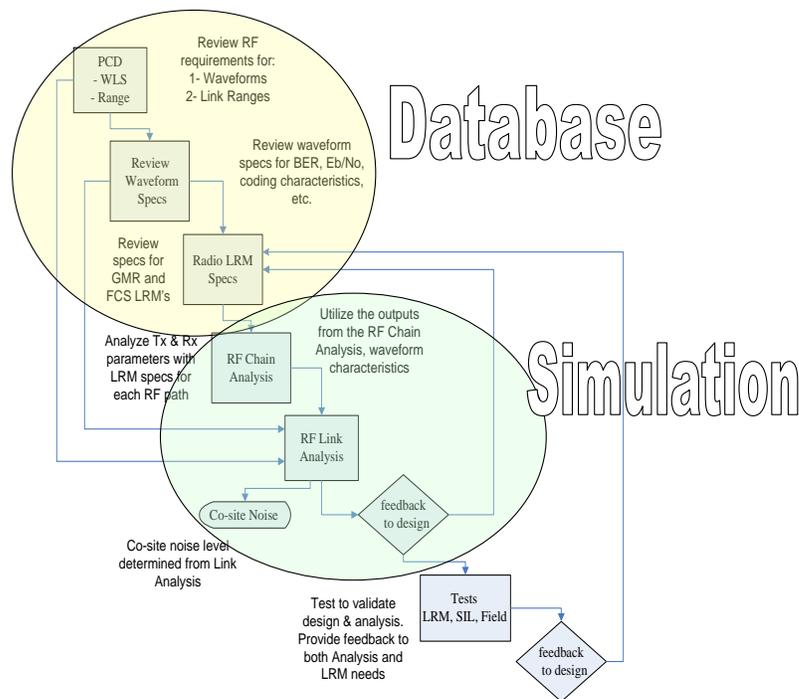


**Figure 4: RF Systems Analysis Context Diagram (Inputs and Outputs of Simulation)**

The technical objective for the cosite analysis includes understanding the limitations in system performance caused by the cosite interference problem, determining the dominant cosite effects that would degrade system performance, modeling system performance under cosite conditions, and generating recommendations to integrate the cosite mitigation schemes into the system design taking into consideration the worst case platform deployment.

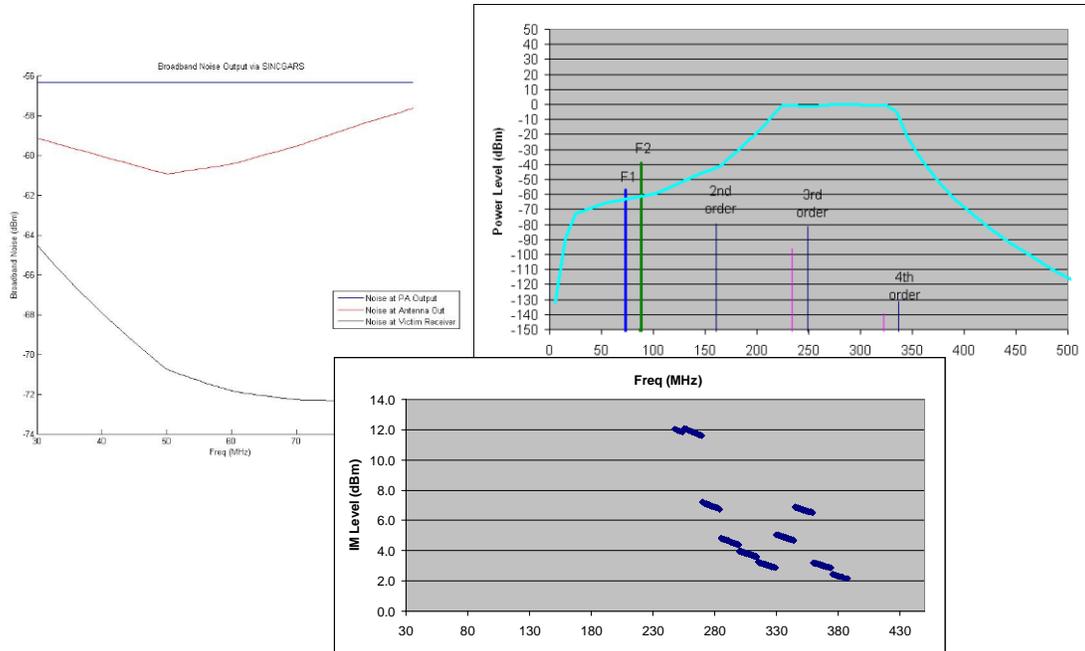
### Process and Tools

Unfortunately, there aren't readily available tools for a RF topside platform integrator to go to. The current tools (or analysis services) have been developed for a specific application and do not have the flexibility to address varying installations. BAE Systems has developed a suite of tools and subject matter experts who have been working ground based communications for many years.



### Figure 5: Analysis Process

Through the process of requirements management, intimate understanding of radio parameters, the system (RF cascade analysis) architecture and test/measurement (model validation) shown above, we have specific knowledge of the mechanisms that cause the destructive collaborative interference. Some typical outputs of our studies are shown below.



**Figure 6 Example Outputs: Broadband Noise, Passive InterMod and Intermodulation Plots**

After Surveying and gathering data/characteristics of all platform/vehicle receivers/transmitters, a cosite matrix is constructed. The layer 1 matrix includes combinations of radars, sensors and vehicles with communications payloads for platforms/vehicles of interest. The layer 2 matrix is constructed for each platform/vehicle. The rows and columns include all emitters and receivers for both communications and non-communications payloads. Rows represent interference sources and columns represent potential victims. Link priority is assigned to each link pair to determine the interference effects on overall system performance. The table below is a sample interference matrix for Intra-Platform.

		Example Vehicle										
		Comms Elements					Sensor Elements					
		Item	#	2	1	1	4	1	1	1	1	
Example Vehicle	Comms Elements	JPR8 MBA VHF/UHF Antenna/L-band Antenna	2	Cosite noise = -95 dBm;; System performance degradation due to Cosite interference: Comm range reduced 25%; BER>1E-6	Cosite noise = -90 dBm; System performance degradation due to Cosite interference: Comm range reduced 30%; BER>1E-6							
		JPR6 225-400MHz UHF DAMA Antenna	1									
		JDR6 1227/1575 MHz GPS Antenna	1	Cosite noise = -90 dBm; System performance degradation due to Cosite interference: Comm range reduced 30%; BER>1E-6								
	Sensor Elements	Short Range EO/IR Sensor on External gimbal with lift/stow & armor	1	Cosite noise = -98 dBm; System performance degradation due to Cosite interference: Comm range reduced 30%; BER>1E-6								
		Multi-Function Radio Frequency (MFRF) System Antenna (w/armor)	4									
		Acoustic Sensor	1									
		Combat Identification System Transceiver (CIS)	1									
		Combat Identification System Transponder Antenna (TAS)	1									
		Combat Identification System, V-Band X-Band/IR/ANT-INTER-BCIS)	1									
		Mine Detection Sensors Type I (Full provisions for payload prime item)	1									
Med Range EO/IR Sensor external gimbal with lift/stow & armor	1			Cosite noise = -98 dBm; System performance degradation due to Cosite interference: Comm range reduced 30%; BER>1E-6								

Table 1 Sample Intra-Platform Interference Matrix

(3) POST RECEPTION SIGNAL PROCESSING

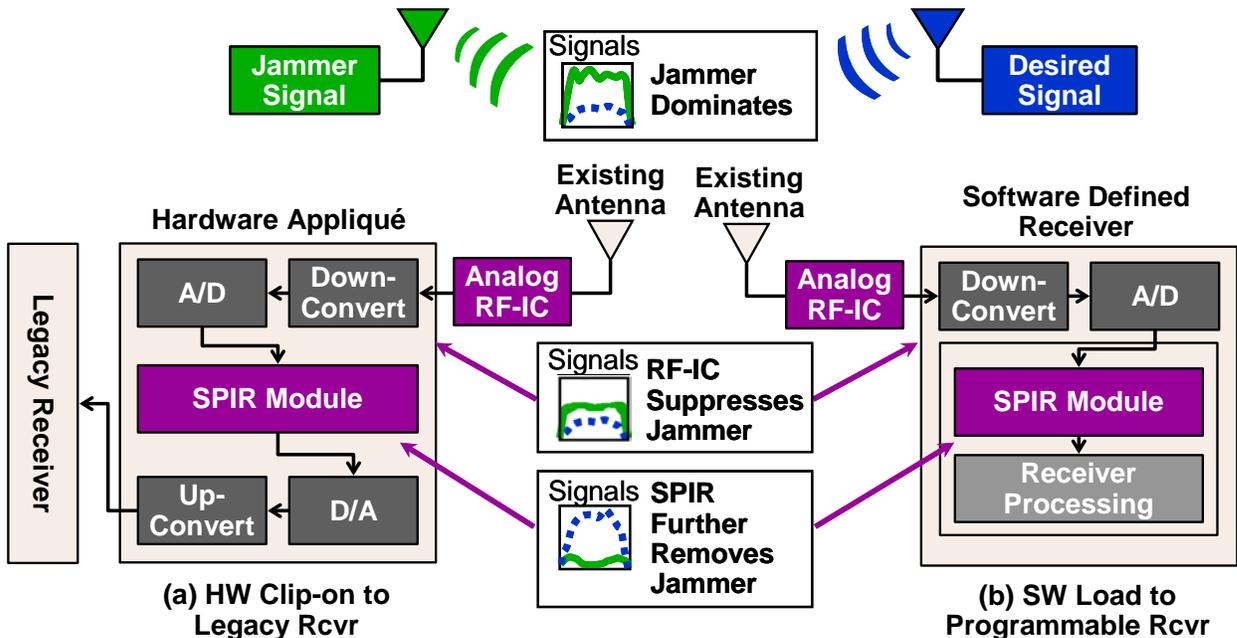
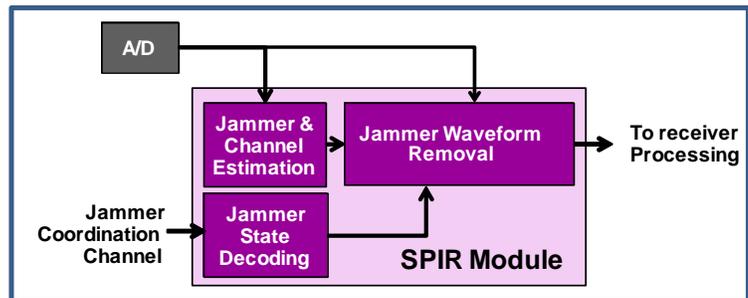


Figure 7. SIPR module can be realized in older systems using a hardware appliqué and in new software-defined radios using software or firmware to achieve jammer

After the antenna and receiver front end overloading is addressed, digital signal processing (DSP) is used to further improve the robustness against the strong interference signals. This Signal Processing based Interference Removal (SPIR) module leverages signal estimation and tracking algorithms, real-time subspace interference suppression, and Multiuser Detection (MUD) algorithms. The SPIR module provides accurate interference estimation, tracking and removal that cannot be achieved with analog RF-IC techniques alone. At the front end of a receiver, the interference signal is overwhelming the desired signal (e.g. blue force comms). The RF-IC module may cancel some of the interference to keep the RF front end from saturating but the residual interference signal is still stronger than the signal of interest. Next the signal is converted to digital baseband where the SPIR module, shown in Figure 8, estimates and tracks the remaining interference signals to digitally remove them from the desired signal.

As shown in Figure 7 the SPIR module can be installed as either a hardware or software appliqué to existing communications systems and SIGINT receivers enabling simultaneous operation during jamming. As a hardware appliqué, the SPIR module enables legacy radio or SIGINT systems to operate without modification to their internal structure. As a software module, the SPIR module provides software-defined systems with improved performance in the presence of interference through a software/firmware upgrade.

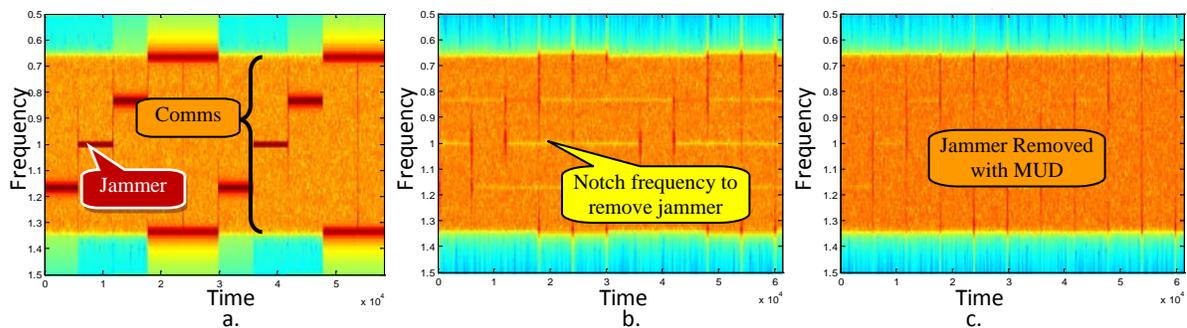
In addition, Multiuser detection (MUD) are used for the interference waveform suppression. MUD is a technique used in digital communications that breaks from the traditional view that other users in the same bandwidth at the same time should be treated as random noise (e.g. CDMA). MUD uses the fact that the other users are transmitting information bearing signals that have a defined structure. Using this model, receiver structures that simultaneously estimate and track the information signals from all users can operate with much better throughput and lower probability of error [1], [2], [3]. The adaptation of MUD for interference signals is quite natural as modern, digitally generated interference signals are created from well-known building blocks, e.g. tones, chirps, pulses, etc. Communication signals are actually harder to remove because we don't know the information that is being sent. Interfering signals don't necessarily encode unknown information in their signal, meaning that if we know the structure of the jamming signal then there is theoretically less impact on receiver. This can only be exploited if the receiver treats the interferer as a structured signal and NOT as noise. Today ALL standard SIGINT and communications receivers treat jammers as unknown random noise. We propose to change this model.



**Figure 8 Basic elements of the SPIR Module.**

To demonstrate how the interfering signal can be removed, we now show how one MUD algorithm, called successive interference cancellation (SIC) is used to reduce the impact of a stepped tone generator on a communication signal with a jammer to signal ratio (J/S) of 40 dB. For this simulation we create a digital communication signal with a stepped tone generator that steps a quarter of the band every 10- $\mu$ s. Figure 9a shows a spectrogram of the received signal before the interferer is removed. Using a current state of the art approach (tuning a bank of notch filters) to remove the interference is somewhat successful, as you can see in 9b. However, the interferer is not completely removed and the filtering causes significant distortion to the communication signal because the impulse response of the filter required to create deep nulls is very long which, in turn, creates very long inter-symbol interference for the comms. This technique can be thought of as removing or nulling the signal subspace where the interfering signal is strongest and using only the signal space orthogonal to the interferer for comms (or sensing). This is effective for some jam waveforms and at some power spreads between the jammer and the desired signal but it does create unwanted distortion.

In contrast, the SIC MUD algorithm makes a blind adaptive estimate for the interfering signal and subtracts off the interferer estimate from the received signal. We call this a blind estimate because the SIC is not informed about the frequency or timing of the interferer. The result of using the SIC is shown in Figure c where the interferer is suppressed by over 40 dB without creating significant distortion in the communication signal. The jammer signal is not completely suppressed when it switches between frequencies due to the blind nature of the estimator. Despite this, the jamming signal is removed during a significant portion of the time and the receiver is able to decode the communication signal.



**Figure 9. The spectrogram of a communication signal being jammed by a stepped tone jammer. Figure b shows the spectrogram after the jammer is removed using the current state of the art. Figure c shows the spectrogram using a SIC MUD realization of the proposed SPIR.**

In Figure 9a the jammer perfectly jams the communication signal causing a 50% bit error rate (BER) when the receiver uses standard digital demodulation and forward error correction decoding without a SPIR module. In contrast, if there

were no interferer the signal has sufficient SNR to be received at  $10^{-9}$  BER. The conventional technique of using tunable notch filtering only reduces the decoded BER to 20%. Using a SIC receiver to remove the majority of the interference followed by a legacy receiver and decoder yields a BER of  $10^{-6}$ . This demonstrates that communication is possible in the presence of interference if the interferer is accounted for in the demodulation process. It is possible that the BER with the SIC could be driven even lower if the distortion created by the SIC were equalized. Methods to remove this distortion and optimally suppress the interferer will be examined on the program. It is important to note that the distortion metric used will depend on the mission to be accomplished (e.g. SIGINT and geolocation receivers will have different distortion metrics than communications receivers).

As an extension to the blind SIC algorithm used above, a model based MUD can be used. If the receiver knows the specific jam waveform being used it can synchronize in time and frequency to remove the signal more accurately. In the previous example this means that the communication signal could have been further improved if the interference canceller were informed of the start time, dwell time, and frequencies being used by the jammer. Informing the receiver about the frequencies the jammer will use and when the transitions will occur allows us to remove the vertical lines in Figure c where interference is not removed due to frequency switching. In the extreme case where the jammer is very dynamic and seems unpredictable, blind MUD techniques become impossible. To overcome this, the receivers must use the side information about what jamming techniques are being used, provided by the jammers or estimated separately. This is an effective technique for ensuring that the jamming signal cannot be blindly removed by an enemy without prior knowledge of the parameters that are shared through the jammer information transmission function.

## **Summary**

A disciplined, systematic approach needs to be taken when integrating RF emitters on any vehicle. Proper antenna placement, understanding the noise characteristics and their effects on specific equipment, and the ability to post process data are all tools available to the RF Topside Architects.

Our three step approach of proper selection and placement of Advanced Antenna Structures, overload protection via active RF cancellation and the further refinement of the signal through the use of Digital Signal Processing is a step in solving this complicated integration problem.

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