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INTEGRATED C4I ANTENNA SYSTEMS FOR TACTICAL AND COMBAT VEHICLES

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ABSTRACT

Antennas are critical to providing digital connectivity to our warfighters. Military mobile networks are much more constrained in operation compared to commercial wireless networks. Military vehicles are limited in size, and must support a large number of different radios. Challenges to both the network and the mobile vehicles require antennas to perform to higher standards. Antenna performance tradeoffs are presented, along with a description of antenna integration methods and emerging technologies to solve integration challenges.

INTRODUCTION

Digital Communications are a part of our daily lives. Nearly 100% of our citizens regularly use mobile digital devices, supported by a robust communications infrastructure. Due to the stability and evolution of wireless infrastructure, very little is required of the antennas built into mobile devices.

Digital communications are a reality for our warfighters too. However, their operational environment is much more challenging. There is no robust fixed infrastructure in most areas of operation. The additional burdens of communications security and high interference require extra margin in mobile connections. Ultimately, this requires antennas on military platforms to exhibit far better performance than similar antennas on commercial devices.

COMMERCIAL WIRELESS NETWORKS

The deployment of wireless networks has taken place at a breathtaking rate. From modest beginnings a few decades ago, the number of cell sites in the United States has grown to more than a quarter million installations in 2010. The number of sites continues to grow.

The sheer number of sites ensures that in almost every imaginable location, mobile users are in close proximity to numerous network access points.

The sites have evolved through several generations of wireless technology. Sites are optimized to provide easy access to mobile users, and to compensate for the effects of propagation. These effects include extreme variations in signal level that can occur due to mobile operation of small antennas.

Quality of service through wireless networks is monitored. Network operators continually improve the networks to provide high quality service to large numbers of users.

All of the cell sites are placed at fixed locations. Coverage is tailored by a mix of cells ranging from small repeaters on the sides of buildings and structures, up to dedicated towers that are several hundred feet high. These sites are integrated into networks that provide access to mobile users.

This wireless network is supported by an equally impressive backhaul network. There are over 300 million miles of fiber optic cable in the United States. This infrastructure provides enormous capacity and connectivity to the wireless networks. This backhaul network is in place in a relatively benign environment.

The objective of wireless network operators is to provide a high quality of service to a very large subscriber base. High quality of service from the network translates to ease of access and use. When subscribers have a good experience, they come to rely on their mobile devices, and increase their usage.

Commercial Wireless Antennas

Antennas on mobile devices must be as small as possible, and still enable the user to keep up an acceptable link to the network. Handsets and other mobile devices are very cost sensitive, and ultimately, mobile antennas are designed to aggressive cost limitations.

The first handsets used small whip antennas. These have evolved into printed circuit boards or folded metal devices that are incorporated into the handset. This further constrains the antenna size, and requires shielding of the transceiver and electronics of the handset. The entire device is housed in a molded plastic enclosure that is transparent to RF radiation.

Once the antenna is integrated into the handset, the radiation patterns are far from ideal. Also, the use of the handset often impairs the antenna further, operating in close proximity to the user, inside buildings, and inside of moving vehicles. These types of antennas are able to provide quality service, even under such conditions, primarily due to the very robustness of the wireless networks. Several wireless antennas are shown in Figure 1, integrated onto a cellphone board.

Figure 1: Wireless Antennas.

MILITARY OPERATING ENVIRONMENT

Military communicators face unique operational challenges. Virtually every part of their networks must be mobile. Military communications require encryption. Radio transmissions must be agile, incorporating waveforms that make it difficult for opponents to intercept or disrupt communications. Many sources of interference are present in the operating environment, both intentional and unintentional.

All of these conditions add more randomness to communication links that are already strained. These conditions necessarily require compensation in the form of additional link margin. This can be managed by all radio components in the link, and place a particular burden on optimizing antenna performance.

MILITARY NETWORKS

A reliable mobile network typically is not available where military operations are conducted. There is no fixed backhaul infrastructure with high capacity. There is no solid wireless access infrastructure that is equivalent to the commercial wireless networks in the United States.

Due to requirements of mobility, military networks are more typically set up with a mesh type architecture. Most radios are used not only for mobile access, but are also used as relays. With all access points in motion, the ability to join a network and maintain connections is more difficult than in a fixed wireless network.

Under such conditions, there is no margin provided by the network to the mobile users. Small antennas used in commercial wireless devices do not have the performance necessary to operate in a military environment. Unlike the commercial wireless networks, the military network itself cannot compensate for the marginal or even poor performance of mobile antennas.

MILITARY VEHICLE ANTENNA SYSTEMS

With a large number of constraints on military networks, mobile antenna performance is critical to reliable communications. The vehicles also have constraints. Space is limited, the operating environment is very difficult and the quantity and variety of radio systems on vehicles is ever increasing. These challenges are not unique to ground vehicles. The same could be said for aircraft and surface ships. Antenna system integration has long been integral to the development and integration of aircraft and ships. Similar challenges on ground vehicles can be met by application of antenna system engineering principles and practices.

Antenna Size

Antennas are tuned to operate at specific frequencies. The physical size of an efficient antenna, at least in one dimension, is on the order of one-quarter to one full wavelength. If an antenna is smaller than one-tenth of a wavelength, it is considered to be an “electrically small” antenna. When using conventional materials and methods, electrically small antennas have limited applicability.

Vehicles have a limited amount of room to install antennas. Planning the antenna integration early in the vehicle design cycle is a critical to optimizing the performance of the vehicle communications suite. It is best to perform vehicle trades early, rather than attach antennas onto a vehicle at the end of the design cycle. This process will make best use of the limited space on the vehicle.

Cosite Interference

Antennas are intentional radiators. The trend has been to install greater numbers of antennas on mobile vehicles. In many cases, the radiation from one or more antennas unintentionally couple back into other antennas on the same vehicle. This is known as cosite interference. In an ideal installation, all radios can be used whenever or wherever the operator chooses. In reality, cosite interference can restrict operation. The antenna system integrator must employ practices that mitigate the effect of cosite interference, with the objective of enabling the maximum utility out of the suite of radios in the vehicle.

Antenna Installation Challenges

Antennas interact with the structures in their vicinity. For any individual antenna, there are optimal methods of installation that ensure best performance. For instance, a monopole antenna requires a substantial ground plane. Whereas, the antenna can be approximately one quarter wavelength tall, ideal patterns assume an infinite ground plane. A ground plane of three wavelengths in radius is a reasonable approximation of an infinite ground plane [1].

Consider a monopole designed to operate over 30-88MHz that is 4 foot tall, close to one quarter wavelength at the center frequency. A three wavelength radius ground plane would be 24 feet in diameter. Clearly, few if any ground vehicles have this type of space for an installation.

Given the limitations of physical mounting space, many antennas are mounted close to the edge of vehicles. This presents a very small ground plane to the antenna, and what is available is often not uniform. Interaction with such limited ground planes can and does considerably affect the radiation pattern [2].

Also, most vehicles have structures, systems and equipment mounted to their exteriors. These can take the form of large structures that block antenna radiation. In this case, placement of the antenna will determine how well it works on the vehicle. Electrical and electronic systems on the vehicle exterior have the potential to cause emissions in the antenna operating band that can interfere with the radio. Antenna placement can eliminate or mitigate these interferers. Integrated filters can provide additional mitigation.

THE IRON TRIANGLE OF ANTENNAS

For a given physical size, an antenna has an operating frequency where it exhibits high efficiency. Efficiencies can approach 100 percent over a fairly narrow range of operating frequencies. The operating range of frequencies is known as the bandwidth of the antenna. The parameters of size, efficiency and bandwidth are the iron triangle.

Antenna Tradeoff Example #1

In this first example, consider a small antenna that is designed to radiate efficiently over a hemispherical region. The pattern approximates a half-sphere, with minimal gain variation above the horizon. Most mobile antennas are designed with this type of performance to maintain a consistent link while in motion.

For a given antenna size, it is possible to increase the operating bandwidth, but only at the expense of reduced efficiency. Take for example an antenna that operates over a band of 400-500 MHz, and occupies a space of 125 cubic inches. An antenna of this description could be designed with an efficiency of over 90%. Assume that the antenna is to be modified to operate over a wider band, such as 200-500 MHz, but cannot be increased in size. This requires a bandwidth increase from 22% to 86%, a ratio of nearly four to one. The efficiency becomes a dependent variable, and is sacrificed to improve the bandwidth.

For a given volume, the gain-bandwidth product remains relatively constant. The antenna gain is proportional to efficiency. In the example cited above, the bandwidth has increased approximately by a factor of four. Correspondingly, the gain will decrease by approximately a factor of 4. This can be expressed as a 6 dB decrease in gain.

Antenna Tradeoff Example #2

The link budget for a given radio connection considers the effects of operating bandwidth, transmit power, antenna gain, receiver sensitivity, propagation loss, unwanted system noise, and interference from other users and systems. All of these parameters are considered when designing a link that provides a specified availability, data rate and quality of service.

In this second example, again consider a small antenna that is designed to radiate efficiently over a hemispherical region. The pattern approximates a half-sphere, with minimal gain variation above the horizon. Many tactical radios are designed to provide a connection with this type of antenna. The parameters outlined above determine the nominal data rate and link quality of a system using this antenna.

Consider that the system designer intends to keep the same transmitter and receiver, and wishes to upgrade the system for increased data rate. With all other variables fixed, an increase in data rate is proportional to the increase in antenna gain. In turn, the increased gain requires an increase in the physical size of the antenna. This also follows because of the constant nature of the gain-bandwidth product.

Thus, the antenna is increased in size to achieve additional gain which enables higher data rates. The antenna grows not only in size, but in complexity. The higher gain beam is more focused, and must be steered when the vehicle is in motion. The primary message is that an antenna cannot arbitrarily be redesigned for increased gain while maintaining the same physical size.

Tradeoff Conclusions

It is important to understand the limitations on physical size before assigning space to antennas. First, the vehicle integrator must consider how much space is needed for all of the antennas that are to be integrated. Second, it is important to understand not only how much space is required, but how to locate the antennas to minimize interference and maximize the performance of the radio systems.

OPTIMIZATION OF VEHICLE ANTENNA SYSTEMS

Historically, antennas have been installed on vehicles nearly as an afterthought. Vehicles had few radios, so interference between antennas was managed by informal methods. Antennas were installed in locations that were convenient from a mechanical perspective, but not necessarily optimal for antenna performance.

Today, there are many more radios and other RF systems on vehicles. Old empirical methods of locating antennas on vehicles are no longer sufficient. Fortunately, antenna system integration has developed on other platforms such as aircraft and ships. These methods apply equally well to ground platforms. Sophisticated modeling tools are now available, and their use eliminates the guesswork and uncertainty of old methods.

Antenna system integration considers methods of optimizing individual antennas, methods of installation to optimize antenna performance, and methods to mitigate or eliminate electromagnetic interference.

Antenna Diversity Parameters

Antennas, first and foremost, are designed to exhibit properties that enable the radio systems to reliably make link, and to continue to maintain the link while on the move. Beyond the functional requirements, the antennas must not connect to unwanted systems. When receiving, any other emitters within or close to the operating band of the antenna can cause interference to degrade or disable the connection. When transmitting, the system can cause unwanted disruption to other systems, or can radiate energy to an adversary.

Given the above mentioned difficulties of interference, it is important to control the radiating environment to the maximum extent possible. Antenna performance can be optimized through the use of diversity. That is controlling certain operating parameters that affect the performance of the antenna in its operating environment. Five diversity parameters and their effects will be discussed.

Frequency diversity is employed by separating antennas by operating band. Physically separating antennas that are close in operating frequency provides maximum path loss. Incorporating filters directly into the antennas, or between antennas and radios, decreases the amount of undesired signal coupled between antennas on a vehicle.

Space diversity is also employed by physically separating antennas to reduce coupling. In addition, antenna patterns can be shaped to direct energy toward the desired link direction, while directing reduced gain or even nulls toward potential interferers.

Polarization diversity is applied by selecting antenna polarizations that are co-polarized toward wanted connections, and are cross-polarized toward potential interferers. This is often applied to satellite links to prevent adjacent satellite interference or to provide additional channel isolation.

Time diversity is applied by transmitting and receiving at different times. In some cases, it can be applied operationally. Two systems may be close in frequency, but are not operated at the same time. In this case, it is possible to locate the antennas close to each other, or even share an antenna with two systems. In other cases, the systems use time division duplexing, transmitting and receiving on different time slots. Thus, antennas only need to incorporate enough isolation to prevent the transmitter from causing damage to receive components. There is less need to provide isolation for simultaneous transmit and receive operations.

Processing diversity is applied to the waveform itself. Spread spectrum communications separate individual sessions through unique coding algorithms. Decoding of a desired signal tends to spread out the undesired signals during the decoding process. The processing gain enables operation in the presence of noise and interference. Systems that employ these waveforms are less susceptible to interference coupled into the antennas, thus enabling more options for locating an antenna on the vehicle.

ANTENNA INTEGRATION

Antenna integration starts with a list of the radio systems that are to be installed on the vehicle, along with their associated antennas. The required antenna gain, efficiency and bandwidth are derived from the overall system link budget. These antenna performance parameters will ultimately determine the approximate physical volume of the antenna. This process is repeated for each of the systems on the vehicle, and the antennas associated with these systems.

Many of the antennas may have already been developed. In the case of these off-the-shelf antennas, it is necessary to provide a location on the vehicle that enables the best link performance. This considers the antenna performance not in an isolated ideal condition, but as actually installed on the vehicle.

Some of the antennas may not yet exist, and are to be developed either for similar applications on multiple vehicle types, or even specifically for one type of vehicle. Again, these must be located on the vehicle to enable best link performance.

Ultimately, a baseline antenna suite is defined, and all antennas are assigned locations on the vehicle. If all goes right, there is adequate space on the vehicle for all antennas and all of their associated systems exhibit acceptable performance. Due to physical limitations, however, there may not be room for all of the antennas, or locations may not be optimal. All of the radio systems may not perform optimally. If this is the case, the antenna integrator must work on optimization.

ANTENNA OPTIMIZATION

Optimization involves the use of design trade parameters as well as antenna diversity parameters to get the optimal performance out of all systems on the vehicle. In general terms, this could be described as enabling the operator to get the most usage from all radios on the vehicle without being encumbered by unintended interference.

Consider a baseline installation that is limited in physical space on the vehicle. This may result in not having enough space for all of the antennas, or in having insufficient performance because the available spaces are not adequate.

One way to correct this is to incorporate multiple functions into a single antenna enclosure. This can be accomplished by nesting antennas, one within another. This provides the function of two or more antennas within the space normally allocated for a single antenna.

This has been accomplished in a conformal antenna for the Expeditionary Fighting Vehicle. The physical cavity of the antenna is 4 inches deep and 21 inches by 21 inches on the surface. This operates as the UHF Line-of-Sight (UHF-LOS) antenna, operating from 225-400 MHz. An EPLRS antenna is nested in the center of the UHF LOS antenna, operating from 420-450 MHz. A GPS antenna is nested in the center of the EPLRS antenna operating at 1227 MHz and 1575 MHz. Thus three antennas are incorporated into the space normally reserved for a single antenna.

Another way to address space limitations is to design a custom antenna into the structure available. In one case, an aircraft integrator required the addition of a lower UHF-LOS antenna on an existing airframe. There was no space left for the antenna, but the aircraft had an existing camera system installed. It was possible to modify the camera housing into an antenna, and still leave the internal space for the camera system.

Finally, basic materials research is being conducted by corporations, universities and government labs to change the paradigm of physical size, bandwidth and efficiency. The goal of this research is to drastically reduce the physical size of antennas while increasing bandwidth and maintaining efficiency. Results in 2010 are promising, and researchers soon expect to achieve significant reductions in antenna size.

Consider a baseline installation that places an antenna close to a structure on the vehicle. This structure, such as a turret, might allow radiation in one direction, but blocks radiation in another direction. In this case, it may be possible to incorporate two antennas on opposite sides of the obstruction. Rather than one antenna with a hemispherical pattern, each of the antennas exhibits a shaped pattern that covers half of a hemisphere. The radio selects the antenna with the preferred coverage, or a diversity combiner makes best use of the combined signals.

ANTENNA MODELING

There are many commercial modeling packages that are used in the design of antenna systems. These allow a designer to define the physical properties of the antenna and numerically derive the RF performance. This is ideal for developing antennas. Many design iterations can be run before committing to the fabrication of hardware. The programs have advanced graphical interfaces that show 3D patterns and current distribution. These graphical constructs are invaluable in development.

These models can be extended beyond modeling and design of individual antennas. Numerical models of entire vehicles can be created. With these models, the antenna structure itself is part of the model. The models are used to derive the performance of the antenna as installed on the vehicle.

Embedded vehicle patterns can be used to determine the best location for each antenna for establishing and maintaining links. Further, these models can be used to calculate the amount of coupling between antennas on the vehicle, effectively modeling cosite interference. This allows the system designer the opportunity to look at multiple options for location of antennas to mitigate cosite. Also, it affords an early assessment of any additional filters that could be incorporated.

CONCLUSIONS

Military vehicles require communications on-the-move. The number of radios per vehicle is increasing, resulting in a greater number of antennas that are integrated onto the vehicles. Limitations of physical space on the vehicles, and in the space required for the suite of antennas, present real challenges in system performance.

It is important to understand the issues related to antenna performance. To the extent that it is possible, antenna system integration should be conducted concurrent to a vehicle development program, or in parallel with a comprehensive upgrade program. Antenna system tradeoff parameters have been presented. Sophisticated modeling packages are available to integrate vehicle antenna systems.

REFERENCES

[1] R. Johnson and H. Jasik, “Antenna Engineering Handbook”, second edition, chapter 4, section4-8, McGraw-Hill Book Company, New York, 1961.

[2] ibid.