Insight

High-Speed Data Transfer in Rugged Computing Applications

Tom Briere
Mathew McAlonis
Earle Olson
Gregory Powers

Executive Summary

The aerospace and defense industries have demonstrated continually increasing demands for rugged computing implementation. The topic of achieving end-to-end connectivity in rugged embedded computing applications, including avionics and vetronics, is discussed. Packaging challenges and solutions are presented at each critical juncture, including inside the box, at the box wall and in the box-to-box connection. Legacy solutions are compared with the state of the art to highlight the escalating demand and advancement in the practice of achieving high-reliability data transfer.

Introduction

Whether it is voice, video or text, the availability of data—including seamless transfer, high-speed/high-bandwidth processing and management—has become a basic expectation in modern society. The rapid proliferation of data sources and enabling technology has touched all facets of civilization, including the world of aerospace and defense. While most commercial systems do not carry the daily burden of mission- or life-critical purpose, those deployed in aerospace and defense do, and adequate ruggedization of those systems is fundamental in ensuring high reliability.

Ruggedization of electronic systems for aerospace and defense applications has been an exercise in compromise. The systems, typically consisting of printed circuit boards, enclosures and copper or fiber optic harnesses, must function as intended electrically, but are expected to offer stereotypical aerospace and defense reliability that includes greater longevity, durability in adverse environments, and ease of maintenance. Enabling these characteristics drives the engineer to innovative design and packaging techniques in search of the most elegant solution.

The following discussion will review the challenges and techniques associated with providing end-to-end connectivity in rugged computing applications, such as in avionics or vetronics. The examination will take the reader from an originating printed circuit board to its enclosure wall, and from an originating enclosure to a receiving enclosure. Technical hurdles and packaging solutions at each juncture will be discussed for the enabling of high-speed data transfer in rugged computing applications. Wireless connectivity will not be addressed in this discussion.

Board-Level Requirements: Chip to I/O

Today, commercial high-speed connectors are found primarily in industrial applications including data storage, servers, switches, routers, and optical transport equipment. These products offer superior high-speed electrical performance, which requires sophisticated connector designs and often intricate/delicate physical features for the housings and electrical contacts. Although these characteristics are adequate for a relatively benign, climate-controlled office environment, often these products have inherent design margins well suited for use in harsher environments in applications that include radar, digital video, digital infrared, and other data and signal processing [1]. Furthermore, some products can be “up armored” by incorporating metal hardware kits that add extra physical protection to the connector components. TE Connectivity AD&M development engineering has provided up armoring solutions to several production backplane designs including Z-PACK HM-Zd, Universal Power Module, and MULTIGIG RT2 connectors. These ruggedized solutions are called HSR (High Speed Ruggedized) and MULTIGIG Extreme connectors. Commercial connectors, however, are frequently limited in terms of ruggedness with respect to the highest performance demands of aerospace and defense applications. Engineering embedded computing products for harsh military applications requires solutions that are designed from the ground up to give years of reliable operation in extremes of operating temperature, shock, vibration, and corrosive atmospheres. These devices must survive extreme environments such as those encountered in aerial combat and from gunfire shock and vibration where human lives depend on system reliability.

Manned vehicles and aircraft as well as precision guided weapons are able to bring information to the battlefield much faster with today's technology than was available previously. Mounted on long-endurance, unmanned platforms, an array of sensor technologies can deliver the persistent surveillance necessary to find and fix an elusive, insurgent enemy [2]. Information can be sent to who wants to see it, and how they want to see it, directly to the offices of government officials or to the foot soldier in theater. Next-generation defense programs, such as the US Army modernization strategy, have further stimulated the growth of technology in aerospace and defense applications, including next-generation radar systems, unmanned/manned ground vehicles, unmanned air surveillance vehicles that can record high-definition video, unattended munitions, ground soldier systems, mobile command centers, and a state-of-the-art network—all of which drive the need for increased signal processing and data transmission. Once deployed, such Army modernization programs will provide safety and knowledge to our armed forces with unprecedented capability to see, engage, and defeat the enemy on today's and tomorrow's battlefield [3].

Defining the Requirements for Next-Generation Military Backplane Connectors

The paradigms of "ruggedness" and "signal integrity at high speeds" are often contradictory. A connector built to withstand adverse environments traditionally has not performed to high-speed requirements. Thus there exists a need for a connector system that offers signal integrity at high speeds while withstanding increased shock, vibration and temperature levels.

The current vision within TE Connectivity's AD&M development engineering team is to provide ruggedization improvements in the high-speed backplane connector designs through marrying an electrically sophisticated, high-speed contact leadframe with a robust, industry-proven separable contact interface. This configuration can then be packaged in a metal shell to offer an even higher degree of robustness both in the mating interface and in the outer shell of the connector. This resulting connector design must be electrically analyzed with regards to signal integrity performance and then tested to confirm it can withstand the demands of the targeted application environments. Electrical analysis tools include 3D full-wave electromagnetic field simulation electrical modeling, followed by signal integrity verification testing using a vector network analyzer and time domain reflectometer. The new TE Connectivity Fortis Zd connector system provides a path for the next-generation of electronic systems in ruggedized environments to enable better equipment, improved communications, heightened situational awareness, and technologically advanced logistics and training (Figure 1). Table 1 compares three popular backplane connectors from TE Connectivity and illustrates an increase in ruggedization.

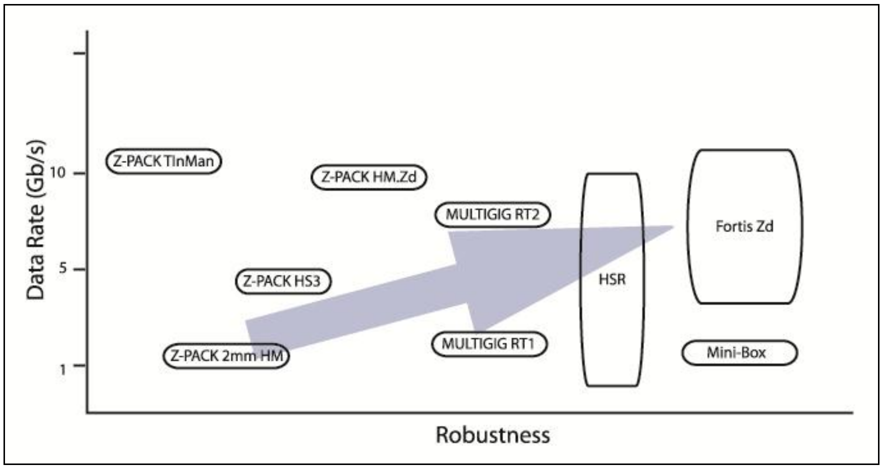


Figure 1. The Fortis Zd connector provides a path for the next generation of electronic systems in ruggedized environments by combining the performance characteristics of high-speed connectors with a mil-qualified contact interface.

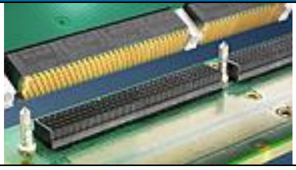
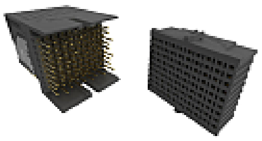
	Connector Family		
	Z-PACK HM-Zd	**MULTIGIG RT**	**Fortis Zd**
			
Standard	PCMIG ATCA	VITA	Based on MIL-DTL-55302
Contact Style	Two opposing "tuning fork" beams 	Two redundant cantilever beams 	Four opposing beams 
Proteced Contacts	Daughter card	Daughter card and backplane	Backplane
Temperature Range (°C)	-65 to 105	-55 to 105	-65 to 125
Temperature Life (Hours)	1000 at 105°C	500 at 105°C	1000 at 125°C
Random Vibrations (Grms)	3.10	11.95	16.91
Mating Durability (Cycles)	250	200; Tested to 2000	500; Tested to 10,000
Mating Force (N, Max Avg/Contact)	0.38	0.75	1.11
6U Contact Density	630 (3-pair config) 840 (6-pair config)	728 (VPX)	900
Seating Tool	Special	Flat rock	Flat rock
Production Status	Production qualified	Production qualified	Production qualified

Table 1. Mechanical attribute comparison of three modern, 10+ Gb/s backplane connector systems illustrating evolution of ruggedness with functional density.

The I/O Challenge

Line replaceable unit (LRU) input/output (I/O) connectors have been rugged for decades. Military flight, followed by high-altitude, high-liability commercial transport, have steadfastly ruggedized the connectors against a myriad of environmental hazards (including vibration, shock, and altitude immersion) and made them human friendly and capable of withstanding many mating cycles and maintenance cycles. However, until the emergence of the internet and the rampant proliferation of high-data-rate protocols, LRU I/O connectors were relatively unsophisticated. Certainly there are some exceptions, primarily custom interfaces driven by military sensors or possibly OEM unique applications, but until the turn of the century, the prefix “giga” was rarely mentioned outside RF technology.

Today it is different. The digital and analog worlds are converging, with RF applications conceding ground. Impedance matching, a longstanding baseline in RF interconnects, has made its way into the digital signal world (see Figure 2). The faster the data transfer, the more important signal integrity becomes, and the less tolerant systems are to impedance mismatch.

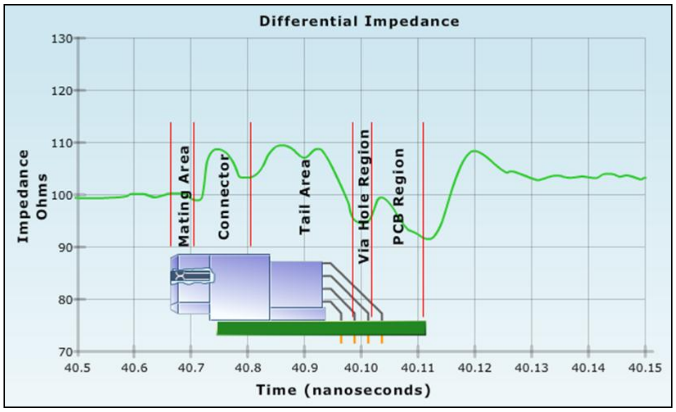


Figure 2. Connector Impedance: Less disruption means higher signal integrity and ultimately higher possible data rates

Everyone wants more bandwidth. Available bandwidth is a function of signal rise time as shown in Equation (1). As depicted in Figure 2, the stability of the signal transmission through the connector is crucial for optimized bandwidth. Very fast rise times stress this relationship and very quickly cull poor connector designs.

(1) $BW = 0.34/t_{rise}$

The I/O challenge then is to provide the same look, feel, and robustness of proven high-reliability interconnects, while baselining minimally disruptive designs, thereby enabling very fast data streams in the most adverse applications.

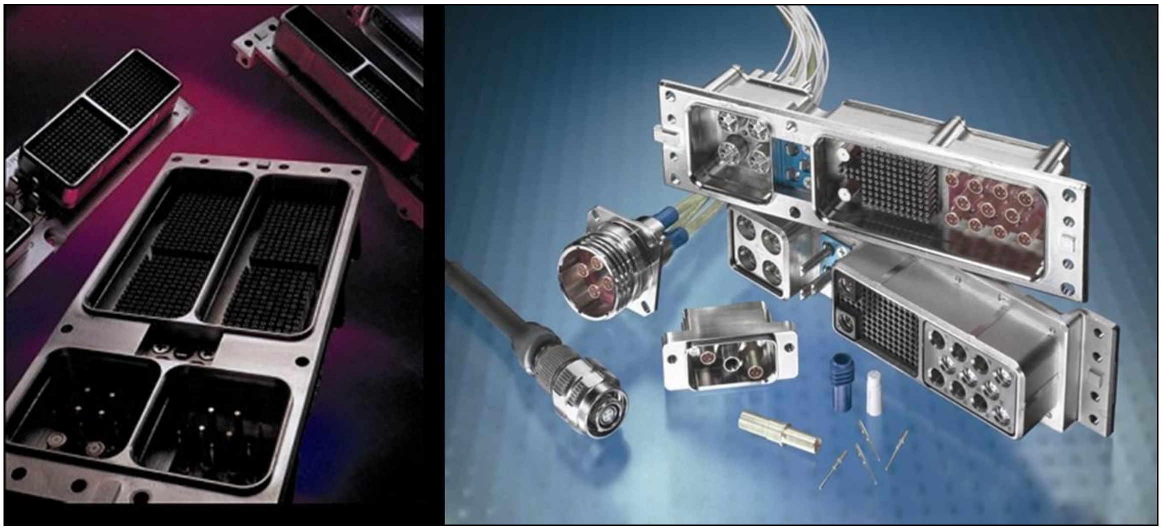


Figure 3. Legacy ARINC 600 connector (left) versus state-of-the-art ARINC connector equipped with inserts for Quadrax and expanded beam fiber optic contacts

A successful, if somewhat early, example of this move to rugged impedance-matched connectors is the Quadrax contact. As data rates accelerated and the need to impedance match grew, engineers began to characterize the old pin fields of military circular and ARINC 404/600 connectors for optimized pin out in an effort to control I/O impedance. This practice proved to be painstaking and highly vulnerable to workmanship variance. Eventually, and as a result of a recent aircraft development program, lessons learned from impedance-matched coax and triax contacts were applied to a new contact leveraging the performance benefits of quad-cable, and the Quadrax contact was pressed forward through the AEEC/ARINC standards organization.

Although this 100 Ohm contact was designed to enable 100Base-T Ethernet, it has been pressed into service for a variety of 100 Ohm applications, including faster protocols such as Gigabit Ethernet. Similar constructions are enabling Fibre Channel, IEEE1394 and USB. As video and other data-intensive applications migrate from RF to digital, additional interfaces, such as HDMI, DVI and DisplayPort™ interfaces, are being managed via ruggedized quads or scalable differential pair interconnects. These applications are being driven faster and faster, forcing the designer to address multiple protocols and manage resulting phenomenon, such as insertion loss, return loss, crosstalk and others, that have direct correlation to impedance and the resulting signal integrity. The name of the game in high-speed data transfer is preserving signal integrity, and the I/O challenge is to keep the I/O interface from being the weak link in the impedance-matched chain.

Figure 4. Field-installable 10 Gigabit Ethernet interface in MIL-PRF-38999 style shell

As demands and protocols have continued to evolve, the future portends more of the same. Higher functional density is needed in order to keep size, weight and power in check. Two solutions remain to overcome the escalating I/O challenge, including highly evolved copper-based interfaces, as exemplified in Figure 4, and the transition to fiber optics.

Relative to copper interfaces, as data streams move into the multi-gigabits per second per differential pair, these will become even more sensitive to subtle variations of design and workmanship. It is likely that field installation and repair will be compromised, with the high speed assembly treated as a line replaceable item. As a waveguide fiber presents its own challenges relative to attenuation, loss phenomenon, and signal degradation. Active devices within fiber optic data streams can be positioned in the box to meet transmit power and receive sensitivity. These are key elements to providing enough bandwidth in a link budget in the I/O connector or in an active cable assembly. There are many packaging alternatives that need to be balanced against mechanical issues such as thermal fluctuations and real-world concerns of maintenance and reparability.

The takeaway from all of these I/O considerations? Even though elegant solutions exist and are continuing to be devised, the designer must be even more diligent in provisioning for both mechanical integrity and signal integrity at the I/O. As signal integrity rises in importance as the primary attribute in connector selection or design, the designer must be aware of mechanical and electrical nuances for assured high reliability performance.

Box-to-Box Connectivity

While it is very common for today's electronic enclosures to run at multi-gigabit per second speeds, enabling reliable high-speed data transfer between enclosures is a daunting task. Addressing the I/O challenge as discussed earlier gets the data to the box wall, but now an entirely new set of issues face the designer. Application drivers include data rate/protocol, distance, environment, weight, EMI/ESD/HIRF susceptibility, installation, and maintenance. These concerns force the designer to assess numerous variables and strive for an optimized balance. In most instances these drivers are interrelated, making the compromises more complex.

The top engineering priority is to deliver the data with necessary signal integrity to the destination. If this is not possible, the application fails. Two areas of concern must be addressed:

- Impedance matching
- Supporting protocol baselines

However, real world parameters must also be assessed:

- What protocol is the most robust for the application?
- What degree of ruggedization is needed?
- How much weight is tolerable?
- Is maintenance expected or is it a non-negotiable customer requirement?
- How will this box-to-box link be installed?
- What are the cost targets?

As box-to-box requirements continue to escalate, numerous high-reliability solutions have evolved in both copper and fiber media. Relative to copper, digital transmission is by far the most prevalent for data transfer and continues to erode legacy analog applications (e.g., video). A voltage differential and therefore some sort of differential pair construction is needed. Over time, it has been determined quad constructions for copper-based cable assemblies are in many cases advantageous for signal integrity over significant distance. This has led to the proliferation of differential pair and quad-based cables to support popular protocols such as Ethernet and IEEE 1394 Firewire. These protocols have their own impedance requirements that must be maintained through the box-to-box connection in order to optimize signal integrity with distance. Additional concerns, such as increasing wire gauge to manage voltage drop, must be considered.

Wire and cable manufacturers specializing in high-reliability aerospace and defense products have engaged their designers to integrate the requirements of today's high-speed protocols with the materials and robust construction techniques developed with decades of deployed experience. As protocols continue to evolve, such as 1000Base-T Ethernet migrating to 10GBase-T Ethernet, manufacturers are working to keep pace and offer ruggedized solutions that support the industry-standard requirements. For copper-based wire and cabling, distance is the greatest enemy. In any case, distance and data rate are inversely proportional. Efforts can be made to fight this battle, such as increasing wire gauge to combat voltage drop, but then weight penalties arise. Designers have many options for box-to-box connectivity in copper-based assemblies, but at some point–as driven by distance, weight and complexity–they are likely to consider the fiber optic alternative.

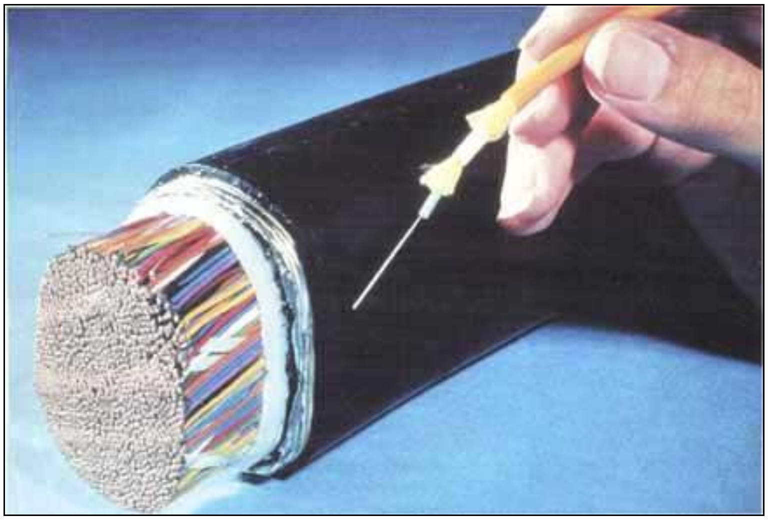


Figure 5. Classic visual bandwidth comparison image: copper vs fiber (Source: Bell Labs)

As the implementation of fiber technology became practical, the multiple advantages of fiber were realized. Figure 5, a classic image from the 1970's, depicts a fiber optic cable next to a comparable bandwidth copper-based telecom trunk line, quickly illustrating the size and weight reduction advantages. This means that fewer cables are needed, fewer repeaters, less power and less maintenance. In addition, fiber is unaffected by the interference of electromagnetic radiation which makes it possible to transmit information and data with less noise and less error. Many of these attributes make fiber a popular alternative for platforms that fly, float and "roll."

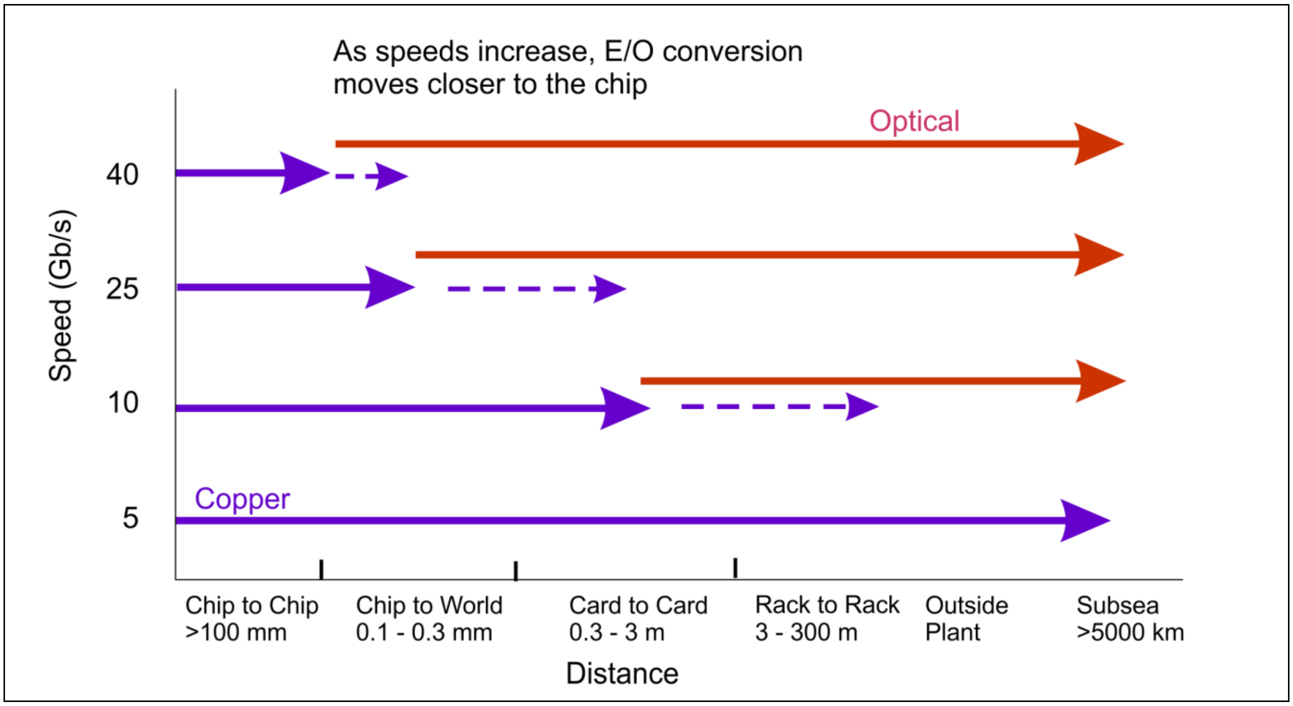


Figure 6. Media, speed, distance, and packaging

From a box-to-box perspective, the accelerating initiative to decrease size, weight and power (SWaP), while increasing the ability of interfaces to handle ever denser sets of signals in both high-speed copper paths and fiber optic paths, is driving packaging trends. Doing all of this without compromising performance raises a set of challenges that are delivering innovative approaches and solutions for the end application and OEM equipment. Figure 6 shows the trend of moving the electo-optic conversion closer to the protocol chips as speeds increase. This leads to the possibility of silicon photonics and radically reduced power consumption at very high speeds. In many instances, the designer hits a threshold, where selection of one technology over the other becomes obvious. Distance is a primary consideration in this tradeoff, but, as discussed, is often intermingled with others like weight, pin count, heat management, materials issues such as outgassing and flammability, maintenance issues, installation issues, ESD/EMI/HIRF issues, cost, and more.

Conclusion

The commercial world is continuing to evolve data transfer protocols and their supporting media at an astonishing pace. Data rates previously measured in kilobits per second have migrated to gigabits per second. High-reliability protocol variations are following this trend at a somewhat guarded distance, as created by the time necessary to assess longevity and to ruggedize the protocol .

As detailed earlier in this document, with appropriate materials selection, application, and characterization, today's solutions involving fiber optic and impedance-matched copper assemblies offer unprecedented levels of reliable performance. Areas of optimization remain, including airworthy extreme-data-rate copper, with its inherent distance limitations and increased shielding complexities, and the incremental improvement of fiber optics, with its temperature, cost, reliability and maintenance trades.

As in the past, new technology with unique attributes is emerging. Materials like carbon nanotubes offer promise to radically change today's design paradigms. However, the laws of physics have not been rewritten and these future solutions will bring their own compromises. Tomorrow's designer will continue to be responsible for managing the trades of bandwidth, weight, size, distance, economics, reliability, maintenance, and more.

The overarching theme to successful high-rate data transfer in rugged applications is to adhere to the longstanding lessons learned for mechanical ruggedization and to optimize impedance matching, preserve signal integrity and characterize the complete channel.

References

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[2] Mercury Computer Systems, Technology Brief, "Tactical Smart Processing: Process, Exploit, and Disseminate the Power of Persistent Surveillance Directly from Sensor to Tactical User."

[3] http://www.bctmod.army.mil/index.html "Army Modernization: Brigade Combat Team."