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The Future of C2

Bridging the Capability Gap for Battle Command On-the-Move

C4ISR/C2 Architecture

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I. Abstract

The U.S. Army recognizes their commanders lack adequate mobile command and control. This capability gap is based largely on lessons learned from ongoing operations in Iraq and Afghanistan. Interim "bridging" capabilities need to be inserted into the current Army force structure until objective systems can be fielded.[1] However, since other Joint services have also voiced similar concerns for improving their mobile command and control systems, the Joint Systems Integration Center (JSIC) has been designated the Joint lead for the federated Joint Prototyping Battle Command On-the-Move (BCOTM) experiment program for fiscal year 2005. This experiment will investigate and evaluate emerging off-the-shelf technologies that can be rapidly adopted and inserted into Joint forces. This technology will focus particularly on improving the warfighter's broadband network connectivity to better enable battle command applications to contribute to the commander's decision-making process while on the move. Modem technologies include direct sequence spread spectrum (DSSS), multi-frequency time division multiple access (MF-TDMA), and frequency division multiple access (FDMA) that employ IP technologies such as Direct Video Broadcast, Paired Carrier Multiple Access (PCMA), and slotted ALOHA. Antenna candidate systems that will be compared include new Ku-band parabolic satellite antennas (apertures equal to or less than 24 inches). The Battle Command Battle Laboratory located at Fort Gordon, Georgia (BCBL-G) is the Army's lead in the Joint federated BCOTM prototype experiment. In this capacity, BCBL-G's primary responsibility is to recommend to an Army acquisition Project Manager broadband satellite on-the-move alternative packaged with doctrine, training, manning, and maintenance strategies.

II. Introduction

This paper begins by characterizing the warfighter's technical requirements and projected operating environments that must be considered when evaluating commercial off-the-shelf technologies capable of providing commanders on-the-move broadband (return 256Kbps or greater) satellite network connectivity. Following this description, a comparison and contrast of various types of modems and antennas technologies are presented that form the basis from which candidate systems are selected for the BCOTM prototype experiment. Modem technologies include direct sequence spread spectrum (DSSS), multi-frequency time division multiple access (MF-TDMA), frequency division multiple access (FDMA), Direct Video Broadcast (DVB), Paired Carrier Multiple Access (PCMA), and slotted ALOHA. Antenna candidate systems compared will include newer Ku-band parabolic satellite antennas (apertures equal to or less than 24 inches) that differ in size, ruggedness, and performance. After introducing and comparing various antenna and modem technologies, an overview of BCBL-G's evaluation criteria and experimental plan (methodology) will then be described. When BCBL-G implements their experimental plan later this year, data collected will form the analytical underpinnings for determining which system and components are viable technologies and offer the lowest

[1] V Corps White Paper titled, "Battle Command Concept, Derived from the Experiences of Operation Iraqi Freedom," Prepared by COL Jeffrey G. Smith, CJTF-7 C6/G6/Commander 22nd Signal Brigade, signed by LTG Ricardo S. Sanchez, U.S Army, CJTF-7 Commander (Baghdad, Iraq), 22 August 2003. p. 13.

developmental and acquisition risks, particularly related to cost, schedule and performance. During the experiment, the BCBL-G will also determine other doctrine, organization, training, materiel, leadership, personnel and facilities (DOTMLPF) solution set required to successfully insert a new BCOTM capability into the current force. This paper will conclude by introducing other possible technologies which are expected to mature over the next 12-18 months and may become future candidate BCOTM systems worthy of further evaluation.

III. Scope

To scope the experimentation, candidate Ku-band antenna and new state-of-the-art modems were initially identified by surveying industry's ongoing research and developmental efforts. As such, candidate components and system selections were based on preliminary review of advertised performance specifications, comparison of technologies, and observations made during several proof of concept demonstrations. Since the BCBL-G formal prototype experiment will not be completed in summer 2005, discussions will focus on how candidate Ku-band modem and antenna technologies initially compare and contrast, as well as, describe BCBL-G's planned experimental methodology and evaluation criteria for determining viable BCOTM technical alternatives/improvements and associated DOTMLPF solution sets.

IV. Warfighter Technical and Operational Requirements

As Joint and Army forces continue modernization efforts toward developing a fully network centric force, improving a commander's ability to acquire updated situational awareness and continually view an accurate picture of the battle space while on-the-move has become essential to achieving information superiority. Under the Army's emerging doctrine and new operational concepts, commanders have information superiority when they are able to "see first, understand first, act first, and then finish decisively."[2] Today's warfighters rely heavily on L-band (INMARSAT) satellite communications for beyond line-of-site network connection while on the move. The L-band system is an expensive leased commercial network service that provides only limited data rates (≤128 Kbps) to mobile command and control (C2) platforms. Objective communications that will eventually provide beyond line-of-site network connectivity for the Army's future force on a noncontiguous battlefield will primarily be Ka-band satellite communications supported by the Wideband Gapfiller Satellite (WGS) constellation. Until WGS constellation is placed into orbit, Ku-band systems that can easily transition to Ka-band are the most logical choice for bridging BCOTM satellite communications technology.

In particularly, Joint land forces are expected to continue increasing their demands for web-based applications and immediate access to Defense Information Switched Network (DISN) to obtain both secure and non-secure voice, data, and video services such as SIPRNET, NIPRNET, CENTRIX, SVoIP, and DSN. While much of the web-based data is expected to be bursty traffic, some time sensitive applications such as video

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[2] Joint/Army Concepts Directorate, Deputy Chief of Staff for Doctrine, Concepts, and Strategy, Objective Force Unit of Employment Concept, (Fort Monroe: Headquarters, U.S. Army TRADOC, June 2003), 28.

and Voice over IP (VoIP), and time-sensitive data will need dynamically allocated bandwidth in order to meet quality of service requirements. Traffic between mobile C2 and stationary nodes, along with a supporting communications hub, will likely be asymmetric in nature meaning that BCOTM applications will demand a higher receive (outbound) data rate (3-10MBps) compared to its transmit (return) data rate requirements (256-512Kbps).

BCOTM platforms must be able to operate in any environment, weather, and terrain. Likewise, BCOTM ground vehicles will likely experience frequent satellite blockage due to foliage, man-made structures, and terrain that will require onboard communications systems to quickly locate, re-acquire, and re-establish satellite communications while moving. In addition, these BCOTM vehicles must be able to re-establish satellite communications regardless of whether they are operating on or off-road. Size, weight, and power consumption of BCOTM Ku-band satellite systems mounted particularly on tactical vehicles must be considered from both a systems engineering and operational perspective. Some tactical vehicles have only limited power and physical space available to which new communications systems can be added. Heavy and bulky satellite systems can also change the center of gravity and safety characteristics of the vehicle. Operationally, tall satellite radomes and parabolic antennas not only can hinder air movement of tactical vehicles and increase the visible signature that may put the vehicle and operators at risk on the battlefield. Given these considerations smaller, lighter, power-efficient satellite communication components are preferred.

The number of mobile C2 nodes needing a BCOTM capability within a highly mobile, network-centric Army Unit of Employment (UEx) continues to increase. A Unit of Employments will replace corps and divisions under the new Army force reorganization plans (i.e. modular forces). Although the current Army requirement appears to be 12 BCOTM C2 nodes for each UEx, this number has occasionally reached 40 nodes per UEx. Future communications architectures will consist primarily of Warfighter Information Network-Transport (WIN-T) communications systems which will provide hundreds of mobile Defense Information Switched Network (DISN) points-of-presence (PoPs) across the battlefield. Under this communications architecture the number of mobile satellite nodes could easily exceed 100 per UEx. To this end, compatible, interoperable, and highly scaleable satellite modem technologies should be used to support mobile BCOTM C2 nodes. As the number of potential nodes increase, the use of bandwidth efficient modem technologies will be needed to control operating costs of leasing Ku-band transponders onboard commercial communications satellites.

In the near-term, BCOTM satellite communications technology will likely require a hub/spoke network topology. As such, the size, complexity, and integration of hub components must also be considered during the evaluation. Although operational placement of support hub equipment has not been determined, initial assumption is that hubs will be installed, operated, and maintained at either the UEx or the Unit of Action (UA) level. If this is true, they would need to co-locate with the new Joint Network Node (JNN). The JNN is a new tactical communications hub being fielding to the Army's reorganized modular forces. If BCOTM satellite communications hubs are deployed and installed in a tactical environment, they must be small (aperture ≤ 4.5 meters), simple, and highly transportable.

V. Candidate Technologies

Understanding the warfighter's technical requirements and the environment in which mobile BCOTM systems will be expected to operate establishes the framework for determining which antenna and modem technologies should be considered as candidate systems. As mentioned earlier, system integration considerations regarding how these broadband systems will compliment existing communications architectures and support the Army's ongoing migratory efforts toward the objective WIN-T solution must apply. Through a series of successful proof-of-concept technical demonstrations that began in fall 2004, combined with the BCBL-G's review of industry's research and development efforts, several promising Ku-band antenna and modem technologies emerged. During these demonstrations, the BCBL-G's industry partners revealed their newest on-the-move parabolic Ku-band satellite antenna systems that were in advanced stages of development. Similarly, industry also revealed several IP modems that employed an outbound Direct Video Broadcast (DVB) with a Direct Sequence Spread Spectrum (DSSS)/Code Division Multiple Access (CDMA) return signal.

During the three proof-of-concept demonstrations conducted at Fort Monmouth, NJ, Fort Gordon, GA, and Suffolk, VA (JSIC), two Ku-band prototype parabolic antennas, combined with new IP modems, successfully transmitted data bursts from a moving tactical vehicle to a stationary communications hub at aggregate rates up to 256Kbps. The data transmitted included FTP image files (streaming video), HTTP (web access), text messages (chat), and blue/red force multicast position data (C2PC). Asymmetric communications from the hub to the mobile nodes reached aggregate outbound transmission data rates up to 3 Mbps. The parabolic antennas demonstrated a capability to quickly track, re-acquire, and re-establish satellite communications after the vehicle experienced intermittent signal blockage while moving. Even though some demonstrations included off-road test routes, antenna performance results remained consistently successful. The BCBL-G received consistent advice from across industry in late 2004 that maturing mobile parabolic antenna design offered the lowest developmental risk compared to other alternative designs such as a low-profile and phased-array antennas; the latter, industry believed to be potentially very expensive.

There are a number of inherent advantages gained by selecting the candidate IP modems that incorporate DSSS/CDMA return technologies. First, these modems reduce the possibility that return transmissions from a small antenna apertures (18-30") will interfere with adjacent satellites, especially in regions of the world where commercial satellite constellations have only 2^{o} separation. Using spreading modem technology enables on-the-move satellite communication systems to comply with power spectral density standards recommended by the International Telecommunications Union (ITU) and required by Federal Communications Commission (FCC). In essence, transmit power from the "disadvantaged" or small antenna is distributed over the entire frequency band of the return channel by adding a pseudorandom bit stream (chipping code), thereby lowering the transmit power spectral density (Watts/Hertz).[3] The higher the chipping rate used in the code, the greater the signal is spread. This is particularly important in the side lobes of the transmitted signal.[4] Another advantage of using DSSS modem technology is that it reduces the probability of interception of the transmitted signal since it is normally difficult to detect the spread signal below the noise floor. CDMA technology also offers increased processing gain that improves the data throughput on the communications link which helps off-set transmit power limitations from mobile satellite terminals. Last, employment of IP modems allows simple physical connection into existing data networks using an RJ-45 connector. The direct layer 3 (IP) asynchronous connection better supports multiple node addressing compared to point-to-point addressing used with existing synchronous serial connections with Frequency Division Multiplexing (FDM) and synchronous Time Division Multiplexing (TDM) network components. This advantage will become further realized once mobile satellite modem technology advances to enable bandwidth on demand across a full-mesh network topology. Moreover, since distributed timing is not required for the IP modem's asynchronous connection, systems engineering to other network components is simplified. The Army's future communications architecture will likely consist of a fully converged IP network that is protected by state-of-the-art High Assurance Internet Protocol Interoperability Encryption (HAIPE) devices which can directly interface at layer 3 with IP modems installed in stationary and mobile communication nodes.

VI. Mobile Satellite Antennas

The BCBL-G will consider three different parabolic mobile Ku-band antennas in the BCOTM prototype experiment. Table 1 below lists a few basic facts and specifications for each candidate antenna systems (A1, A2, and A3). Antenna A1 was

Antenna System	Axis Type	Dish Size (inches)	Total Wt. (incl. mount & radome)	Ruggedness Y-Lab Ku or Ka-band version tested N- Untested	Relative Cost 1-$300-400K 2-$200-300K 3-$100-200K	Proof-of-Concept Demo Y-Successful Participation N-No participation	Peak Power Consumption (watts)
A1	3-axis	24"	75	N	3	Y	600
A2	2-axis	24"	155	Y	1	Y	1500
A3	3-axis	18"	92	Y	2	N	860

Table 1. Antenna Initial Comparison Matrix [5,6,7]

[3] Newton, Harry, Newton's Telecom Dictionary, 19th ed., (San Francisco: CMP Books, 2003), 628-629.
[4] Stallings, William, Data & Computer Communications, 6th ed. (New Jersey: Prentice Hall, 2000), 166.
[5] Northrop-Grumman, Trac-Star antenna specification data sheet. 1.
[6] TriPoint Global Inc., SATCOM On-the-Move brochure, August 2004, 2.

originally designed for satellite TV reception on commercial recreational vehicles. It has been significantly modified to support Ku-band satellite communications on the move. This 3-axis, light-weight and cheaper antenna has been successfully demonstrated in BCBL-G proof-of-concept demonstrations, as well as at other technology conferences and commercial displays. During the BCBL-G proof-of-concept demonstrations the antenna system was required to quickly relocate/re-acquire satellite lock and re-establish communications as the test vehicle constantly varied its speed and direction on and off-road. Additionally, the test vehicle forced the antenna to re-establish satellite lock after experiencing intermittent signal blockage. A1's ruggedness has not been tested on the Churchville B, Perryman 3, or Munson road tests at the Army Research Laboratory (ARL).

Antenna A2 is the heaviest antenna candidate system and it too has proven its candidate potential during a number of technology and BCBL-G's proof-of-concept demonstrations. The size (height with a radome) and weight of A2 require special mounting provisions on tactical vehicles. The preliminary antenna pointing accuracy test indicates A2 potentially could have a very high pointing accuracy because its design was derived from a Ka-band version. Due to the narrow beamwidth, pointing accuracy specifications for Ka-band antennas are much more stringent than Ku-band systems.

Antenna A3 is the BCBL-G's newest 3-axis candidate antenna system that has recently been added to the experimental list. Its size and enclosed cooling system offer vehicle installation and tactical environmental advantages. Even though the Ku-band version of A3 has not participated in live proof-of-concept demonstrations, it has shown significant potential in lab simulation tests. Like A2, it too is a derivative of a Ka-band design that has successfully passed ARL tests. Before it participates in the BCBL-G prototype experiment, it must pass a proof-of-concept demonstration that is planned over the next several months. Both A2 and A3 were specifically designed to operate in a tactical environment offering some initial advantages over A1.

VII. Candidate Modem Systems

The BCBL-G has identified five possible candidate modem technologies to evaluate. Modem (M1, M2, M3, M4, and M5) characteristics and technologies are summarized in Table 2 below.

Modem M1 is an IP/asynchronous modem that uses DVB/Paired Carrier Multiple Access (PCMA) for the outbound signal and DSSS/CDMA/conventional Aloha on the return signal from the mobile node back to the supporting communications hub. This modem requires a hub/spoke network topology. The PCMA allows carrier frequency re-use for full-duplex communications between the hub and mobile node. PCMA is accomplished by the hub canceling/suppressing its reflective power in the receive signal from the satellite. The hub continually estimates the frequency, delay, phase, and

[7] Fredette, Tom, Titan Corp., "Ka-band Satellite Communications Augmentation Terminal (KaSAT) Briefing ," Full Mesh MF TDMA DAMA SHF Communications presented to PM WIN-T Team, 1 March 2005, 16-17.

amplitude of its transmitted (outbound) signal and continually compares this estimation with the actual signal received (return). As the hub suppresses its estimation in the composite receive signal prior to demodulation, it leaves only noise and return signal from the mobile node. This signal is then demodulated/de-spread. Frequency re-use can offer up to 50% bandwidth reduction between a hub and its mobile nodes. In some cases when PCMA is used with power efficient modulation and Forward Error Correction (FEC), it may even reduce the required transmitted power. This assumes that other parameters such as the number of network nodes and data rates remain constant. Overall, the benefits of M1 using PCMA can be realized in bits/sec/Hz. PCMA is a proven technology now employed in commercial applications and largely fixed networks. [8]In low traffic networks DVB can be bandwidth inefficient, since it uses a FDMA technology where large bandwidth is dedicated for full-time broadcasts and cannot be dynamically allocated for other uses. Another disadvantage of DVB is that it cannot not support a full-mesh network topology.

Modem	Connection Type **IP/Asyn**=IP Asynchronous **S**=Serial Synchronous	Media Access Protocol **C**=connection oriented **CL**=connectionless	Network Topology **H/S**=Hub & Spoke; **FM**= Full Mesh; **P2P**=Point to Point	Broadcast (Outbound from hub) **BoD**=Bandwidth on Demand	Return (Inbound from mobile) **CA=**Conventional Aloha; **SL=**Slotted Aloha; **NCW**=Network Centric Waveform/MF TDMA; **BoD**=Bandwidth on Demand: **D**=Dedicated Bandwidth; **MF TDMA**=Multiple Freq Time Div Multiple Access	DSSS Return **Y**=Yes; **N**=No
M1	IP/Asyn	CL	H/S	DVB-PCMA	CDMA/CA-BoD	Y
M2	IP/Asyn	CL	H/S	DVB	CDMA/SA (SAMA)-BoD	Y
M3	IP/Asyn, S (Programable)	CL, C	H/S, FM	DVB	CDMA/NCW-BoD, FDMA-D	Y/N
M4	S	C	P2P	FDMA-D	FDMA/D	N
M5	IP/Asyn	C	FM	MF TDMA-BoD	MF TDMA-BoD	N

Table 2 Modem Comparison Matrix

The return channel from the mobile uses Code Re-use Multiple Access (CRMA) that is a proprietary CDMA variant. It differs from traditional CDMA technology in that

[8] Dankberg, Mark, ViaSat Inc., Paired Carrier Multiple Access (PCMA) for Satellite Communications, (Carlsbad, CA: ViaSat Inc.), VSD-820000-98-009, 1-8.

the same code is used by multiple nodes. Using the same code helps reduce the modem's complexity and cost. CRMA can increase processing gain on a transmitted signal which is important to small disadvantaged terminals that are normally power limited. When M1 has data ready to send it gains access to the transmission medium using conventional random access aloha protocol. The advantage is that a node does not wait to transmit data and experiences minimum transmission latency. In contrast, conventional aloha access protocol by nature is susceptible to collisions when link usage exceeds 10%. If a node does not receive acknowledgement of receipt from the hub, it assumes a collision has occurred and will wait a random period before attempting to retransmit.[9]

M1 employs commercially proven technologies such as PCMA, DSSS, and conventional aloha technologies making it worthy of further evaluation. PCMA technology is now employed in large fixed commercial networks so it will be new to tactical on-the-move satellite communications. M1 uses DSSS signaling to minimize the potential of the transmit power from a small aperture causing adjacent satellite interference. During several proof-of concept demonstrations, M1 successfully provided a mobile node with a 3 Mbps broadcast and a 256Kpbs return signal while the test vehicle was moving. Overall, M1 appears to offer bandwidth efficiencies using a DVB/PCMA broadcast, but these advantages are limited by the inefficiency of using conventional aloha protocol on the return signal.

Modem M2 is an IP/asynchronous modem that uses a proprietary variant of the DVB standard for its outbound signal. Like M1, DVB is well-suited for bursty traffic. The return signal uses a form of slotted aloha random access protocol combined with direct sequence spreading called Spreading Aloha Multiple Access (SAMA). The return channel is divided into Demand Assigned Multiple Access (DAMA) sub-channels within a single frame separated by different carrier frequencies and within a defined bandwidth. For example, a 3 MHz return channel can be subdivided into 15 sub-channels to support a return data rate of 256 Kbps. These sub-channels are dynamically assigned for each frame based on quality of service (QoS) requirements. M2 modem technology requires a hub/spoke network topology. One key advantage is that it offers flexible link configuration for the warfighter. High priority users and time sensitive applications can be assigned one or more dedicated sub-channels to guarantee a committed information rate (CIR). M2's DAMA capability enables the remaining sub-channels to be dynamically allocated to other nodes in the network. In a single frame, each sub-channel carries 96 bytes of data. The hub dynamically reserves each time slot within a single frame and one sub-channel. These time slots are fixed in length and begin at discrete intervals to reduce the chance of media contention/collisions. This technology is two to four times more efficient than conventional aloha used by M1, especially when another node has already began transmitting. Contention on slotted aloha networks occurs when a node competes with other nodes for access control of a discrete time slot at the beginning of a frame. Once the frame is allocated in the network, no collisions are possible until the start of the next frame. Slotted aloha random access protocol is an

[9] Elbert, Bruce R., Satellite Communication Applications Handbook, 2 ed. (Boston: Artech House Inc.), 332-334.

efficient technology when link saturation remains below 36%.[10] However, if link saturation (utilization) on a congested network exceeds 36%, delay and network latency from media contention/collisions will increase exponentially as shown in Figure 1.[11] [12]

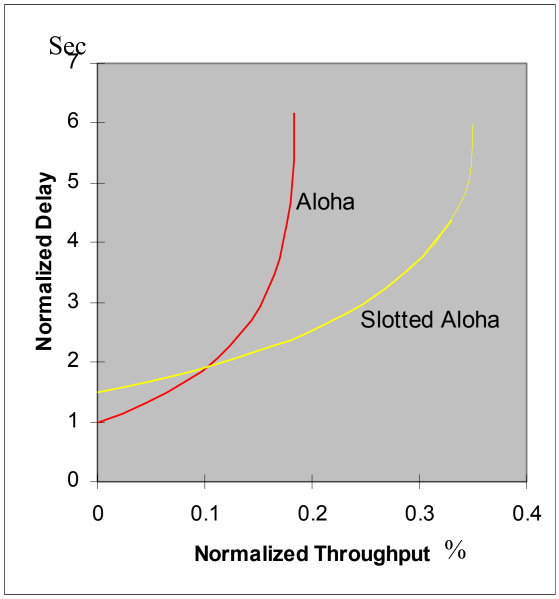

Figure1. Example Throughput Delay Characteristics

Despite some of its limitations, studies from commercial applications reflect exceptional bandwidth efficiency and potential for scalability. The return channel also uses CRMA (CDMA) like M1. M2 was paired with Antenna A1 during BCBL-G proof-of-concept demonstration where the mobile platform successfully received 2-3 Mbps DVB broadcast and provided a 256Kbps return data rate while the test vehicle was moving.

Modem M3 is another candidate IP/asynchronous modem much like M1 and M2. The vendor claims that M3 will be ready to participate in a proof-of-concept demonstration prior to evaluations during the prototype BCOTM experiment. If M3 participates as promised, its planned capability and level of complexity could easily exceed that of the other candidate modems. M3's complexity centers around its ability to employ a software-defined (programmable) network centric waveform (NCW) that must meet WIN-T defined specifications. This modem can be switch to either FDMA or NCW mode of operations. As an FDMA modem, it can support a serial/synchronous connection that enables it to directly interface with existing tactical communications infrastructure.

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[10] Saturation percentage also depends on the type of modulation scheme and forward error correction technique used.

[11] Elbert, 337.

[12] Huffman, Steven H. Dr., "Satellite Communications Systems Briefing," Presented at AFCEA TechNet, Tampa, FLA, 08 March 05, slide #70.

This includes systems now being fielded to the modular Army units and the U.S Marine Corps FDMA communication systems.

In the NCW mode, M3 uses a DVB like outbound signal much like M1 and M2. It differs in that its return channel uses a Multi-Frequency TDMA DAMA (MF-TDMA) with a DSSS signal. The MF-TDMA consists of two transmit and seven receive carrier frequencies for each IP modem. One of the transmit carriers supports Secure Voice Order-wire and the other supports transmission of the return channel. Each modem can receive up to seven channels simultaneously. This capability will enable the node to eventually receive multiple signals simultaneously from other nodes in a full mesh network topology. M3's unique NCW offers it several unique capabilities which are tailored particularly for highly ad hoc networks that continually reconfigure as nodes enter and leave the network. While the mobile is moving, the NCW return signal will use a BPSK modulation in a spreading waveform. At-the-halt or stationary, mobile nodes can use a more efficient Off-set Quadrature Phase Shift Keying (OQPSK) with a non-spreading waveform.[13]

The M3 NCW gives the modem the capability to support a near full mesh network topology. In a true full-mesh network, all nodes can communicate directly with each other without going through a designated hub node. M3 NCW can communicate directly with other nodes for some services such as Voice over IP (VoIP) and video. Other applications require limited hub assistance, but routers and applications only see the virtual connection as a single hop. In this type of network, one node will be designated as a Network Controller (NC) and the other nodes are called Node Members (NM). The NC could be a mobile node or a stationary node. The NC determines how much bandwidth (frame length) and exactly when a network node or NM will be granted media access within each frame. The NC begins by first transmitting a reference signal or beacon (Forward Orderwire-FOW) to the NM in order to estimate signal losses and establish/synchronize the initial network timing. Once a NM receives this beacon, it reports the measured receive signal strength back to the NC using the NM's assigned time slot (Return Orderwire-ROW). The NC then measures the returned signal strength (ROW) C/N_o from each NM in each frame. After all the NMs have synchronized with the NC, payload data packets are sent from node to node. The NC controls key link parameters such as EIRP, data rate, modulation, code rate, and spreading factors on a burst-to-burst basis. Other factors which influence these parameters include node capabilities, fade conditions, and slot types. Contention for media access is managed by adding more time before and after guard intervals that exist between time slots within a single frame. Since there are no fixed carriers in NCW, bandwidth allocation is fully dynamic within a single frame, therefore it is not uncommon for the bandwidth of a single frame to include return transmissions from multiple nodes. In addition, the NCW supports up to 16 data priority levels that aid in allocating bandwidth to meet quality of service requirements. When the M3 NCW fully matures, efficiencies gained in network

[13] Harbison, Bill, Titan Corp., "System Network Architecture Briefing," Full Mesh MF TDMA DAMA SHF Communications presented to PM WIN-T Team, 1 March 2005, 19.

performance will maximize the spectrum close to Shannon's information theoretical limits.[14]

The vendor acknowledges that M3 NCW requires further developmental refinement and debugging for it to reach its full functionality, but remains confident this modem will be ready in time for the BCBL prototype BCOTM experiment. M3's drawback will be the complexity of its design. This clearly could make learning how to install, operate and maintain this modem difficult at best.

M4 is a serial/synchronous modem that uses existing FDMA technology for both its outbound and return signaling. Its serial/synchronous interface into other networks is exclusively point-to-point. A M4 FDMA modem divides users up by assigning them specific carrier frequencies. This gives users full-time, dedicated bandwidth that provides a guaranteed quality of service. Since there is no access contention, network latency is minimized. FDMA is a proven and reliable technology that has been used extensively in tactical environments and currently being used to provide communications at-the-halt in the Army's modular forces. The Marine Corps is also looking at M4 for use in their new mobile CONDOR C2 vehicles. By employing M4 in BCOTM vehicles, it offers direct network connectivity into existing communications infrastructure and provides superb interoperability with key systems such as the Army's new Joint Network Nodes. In proof-of-concept demonstrations, M4 was matched with Antenna A2 where it successfully provided reliable VoIP, web-access, and Blue Force Tracking (BFT) data to a mobile tactical vehicle on the move. Transmit and receive data rates reached up to 2 Mbps.

The M4's FDMA technology has several obvious technical limitations that BCBL-G must consider during its modem evaluations. FDMA is highly inefficient for transmitting bursty traffic. When a mobile node has no traffic to send, its dedicated bandwidth remains idle and cannot be shared with other nodes. Secondly, due to its inability to share spectrum, scaling to a large number of mobile nodes will become cost and resource prohibitive. Since the return signal does not use DSSS as modems M1-M3, complying with ITU standards and satisfying the FCC spectral power density requirements to avoid adjacent satellite interference will be difficult. These types of issues could in turn hinder or prevent obtaining proper licensing and spectrum authorizations from host nations in certain areas of the world. Due to M4's synchronous network connections, link engineering to manage required distributed network timing is often less than straight forward. It requires careful and advanced systems engineering skills to overcome potential timing issues for each component in the communications link. Even though M4 has technical limitations, it remains a viable candidate modem that serves as the technology baseline or "status quo" against which other candidate modems can be compared.

The last modem is M5, an IP/asynchronous modem that uses MF TDMA DAMA technology for its outbound and return signals. The Army is currently using MF TDMA

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[14] Cusano, Mark, Titan Corp., "System Network Architecture Briefing," Full Mesh MF TDMA DAMA SHF Communications presented to PM WIN-T Team, 1 March 2005, 38.

DAMA technology as its primary backbone satellite communications architecture in the Stryker Brigades and the new modular forces. Although this technology has successfully serviced stationary users, it has not been tested in mobile applications. The advantages of using IP modems already addressed apply to M5. A key advantage of this technology is it supports a full-mesh network topology. Network nodes can directly communicate with other nodes without requiring a separate communications hub. In a MF TDMA network users greatly benefit from its dynamic bandwidth on demand capabilities and spectral efficiencies, especially when sending bursty traffic. Data rates as high as 4 Mbps can be allocated between network nodes. Quality of service can also be implemented to support latency- sensitive applications such as VoIP and video. A Master Reference Terminal (MRT) dynamically allocates transmission bandwidth (on demand) and assigns transmission timeslots to all network nodes. The result is maximum data throughput and network performance for stationary users.[15] Initial concerns for using MF TDMA DAMA on moving BCOTM vehicles are related to potential link timing issues. As the mobile satellite system experiences unavoidable signal blockage, network timing synchronization must be re-established before service disruptions can be restored. Although BCBL-G has extensive expertise with MF TDMA satellite communications, it has not demonstrated this technology on a BCOTM platform. BCBL-G will continue to investigate the viability of this technology.

VIII. Evaluation Criteria

The BCOTM evaluation criteria have been divided into three areas; *Test, Model* and *Comment*. The *Test* criteria include aspects of system or sub-system performance which should be tested to provide a performance metric for comparative analysis. The *Model* criteria include aspects of system or sub-system performance for which some performance metric is required, but testing is neither feasible nor practical. The *Comment* criteria include aspects of the system or sub-system for which modeling or testing is not appropriate, but some form of written evaluation must be made in relation to the specified criteria. While the details of each evaluation criteria and method can be obtained from the BCBL-G Test Plan, most of the evaluation focuses on the performance of the antenna and the modem sub-systems.

The ability of the mobile satellite antenna to remain accurately pointed at the satellite without causing adjacent satellite interference is fundamental to the overall performance of the fielded system. Additionally, the complexity of the operating environment ensures that communications between moving mobile nodes and stationary hub nodes will experience frequent signal blockage by solid objects such as telephone poles, trees, vehicles and tunnels. These intermittent outages may be indeterminate in length therefore, the fielded system must be able to cater to outages without having to reset or re-establish a communications pathway on each occasion.

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[15] U.S Department of the Army, 3/2 Stryker BCT, 2nd ID, "Digitally Deployed-120-Day Assessment of Signal in the 3/2 Stryker Brigade Combat Team Operation Iraqi Freedom," April 2004. pp. 4-14.

The antenna testing includes a suite of field tests aimed at quantifying a number of performance metrics, the most important of which are *acquisition time*, *pointing accuracy*, *beam width*, *size*, *weight* and *power* consumption. *Acquisition time* and *pointing accuracy* determine how long it takes the antenna to relocate and correctly point at the satellite before communications can either commence or re-commence after an outage caused by a solid object. A measurement of *beam width* can be used to calculate the power spectral density at the satellite. When coupled with the antenna pointing accuracy, these criteria will ultimately determine whether or not the antenna and modem combination receives ITU and FCC approval to operate without causing adjacent satellite interference.

The *size, weight* and *power* criteria determine the ease with which the fielded system can be inserted into existing vehicle platforms. Noting that the antennas vary in weight from 75 to 150 lbs and power requirements may be as much as 1500 W, all vehicles centers of gravity will be affected and some vehicle power systems may require modification to allow integration to occur. The full suite of DOTMLPF inputs therefore need to be examined for their impact.

Modem testing is primarily focused on the measurement of data *throughput* and *spectrum efficiency*, noting that the limiting factor in the value of the system will be the maximum data rate at which the disadvantaged terminal can either receive or transmit data. Both modeling activities and field trials have been prescribed for modems under evaluation. Initial tests will focus on the use of generated messages in both modes of operation before transitioning to the field testing of ABCS and other applications with the end state being the identification of the most promising of the technologies on offer for integration into existing forces and platforms. Additionally, one of the key modem performance criteria is *scalability* which dictates the maximum number of nodes the system can support. Practical limitations prevent the establishment of a full size test network. Alternative measures will include the combined use of live experimentation and existing communications modeling tools that can provide a means to assess the size of a realistic network (scalability) supported by a specific candidate technology.

IX. BCBL-G Evaluation Methodology

As part of the Joint effort, the BCBL-G evaluation methodology breaks the testing regime into three broad phases, each of which includes a number of defined events. The resources required for the successful completion of evaluation include the test facilities and staffs at JSIC, BCBL-G, and Navy SPAWAR –Charleston, Army test facility (Fort Dix, NJ) and Marine Corps test site (Quantico, VA).

Phase one will include establishing up to five different hubs at BCBL-G, using predominately vendor supplied equipment. The BCBL-G will test separate antenna and modem sub-systems and graduate to systems level tests. All tests will be designed to collect data necessary to validate performance parameters of each component and satellite system. Testing will be conducted as a joint effort between JSIC, SPAWAR-Charleston, Marine Corps (CONDOR Program) and BCBL-G in accordance with the

Joint Test Plan which is still undergoing development. The aim of this testing is to validate vendor systems capabilities, gain a better understanding of system technology, determine component/system performance limitations, and identify system integration requirements.

Phase two will be primarily aimed at testing the mobile node equipment offered by the vendors. This phase will field test all of the antenna performance criteria identified in earlier paragraphs, as well as modem throughput and system performance metrics. This phase critically tests the performance of each vendor system while moving and verify the scalability of the system. The key outcomes of this phase will be a recommendation for the fielded system for insertion into existing forces and insights to DOTMLPF considerations.

Phase three will insert candidate systems into the AAEF and V Corps for user trials on exercises and potential deployment to OIF. This phase will include the live field testing of user applications such as ABCS and collaborative tools, as well as verification and validation of the DOTMLPF solution set within an Army and Joint environment.

Current time lines indicate that the first hub installation will commence at the BCBL-G in late March 2005. JSIC and BCBL-G will complete evaluation of two systems by late June 2005 to allow one to be operationally tested in a V Corps mission rehearsal training exercise in Germany. The other candidate system will be operationally tested at Ft Dix, NJ. Following the experiment, one of the recommended candidate systems will participate in subsequent trials during the Air Assault Expeditionary Force at Ft Benning, GA in the Oct/Nov timeframe. Live experimentation will be used to refine the DOTMLPF solutions sets that will be needed to ensure a successful technical insertion into the current force.

IX. Future Developments

As industry realizes the importance of providing Joint and Army commanders with improved broadband satellite communications for BCOTM, more advanced technology will likely emerge within the next 12-18 months. These technologies include: add-on data compression applications, improvements in the NCW functionality, development of low-profile satellite antennas, and advancements in QoS/IP accelerator devices. One vendor is even developing a product that will combine a router, TCP/IP accelerator, satellite modem, power supply and AES transmission security device all into a single box. Given the time constraints for BCBL-G to complete its BCOTM experiment, candidate technologies are limited to only those available within the next 3-4 months. The BCBL-G will need to conduct follow-on experimentation in 2006 to evaluate developing technologies that can improve near-term satellite on-the-move solutions. These new technologies open opportunities for further research, particularly in technologies that maximize bandwidth efficiency on tactical on-the-move communication systems. After the completion of BCBL-G's BCOTM prototype experiment in summer

2005, collected data will be analyzed to determine which candidate antenna and modem technologies the BCBL-G will recommend to an acquisition project manager.

XI. Conclusion

The BCBL-G has selected candidate modem and antenna technologies that offer the highest potential to satisfy the Joint BCOTM prototype experiment objectives. The BCBL-G chose candidate systems primarily based on their successful performance during proof-of-concept demonstrations. These candidate systems will enable the BCBL-G to determine viable near-term technical solutions for BCOTM that can improve the warfighter's capability to maintain mobile battle command and situation awareness on the modern battlefield. The aggressive experimental timeline, enhances the probability that recommended technical solutions benefit units preparing to rotate back into Southwest Asia.

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