FCS Communications
Technology for the Objective Force

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ABSTRACT

As part of its technology development program for the Army's Future Combat System (FCS), the Defense Advanced Research Projects Agency (DARPA) has been working to develop the enabling communications technology needed to revolutionize the Army's future land force into a network centric force capable of operation at a level of synchronization, mobility, and force effectiveness which has been heretofore unachievable. Key to this network centric operation will be a scalable suite of multiband wireless, mobile adhoc networking devices which operate with directional antennas to provide significant improvements in capacity, Anti-jam, and Low Probability of Detection (LPD). This paper reviews the underlying motivation for this technology development and summarizes the numerous technology investments being made by DARPA under their FCS Communications technology program.
Keywords: MANET, wireless, mobile, networks, directional, propagation, AJ/LPD

1. INTRODUCTION

Joint Vision 2020 (JV2020) identifies our nation's objective of fielding an effective and efficient multi-mission force capable of projecting overwhelming military power worldwide to achieve full spectrum dominance. This force must provide our nation with an increased range of options in responding to potential worldwide crises and conflicts. To meet this objective, the U.S. Army has committed to transforming itself into a Twenty-first Century full spectrum fighting force.

As part of this transformation, the Defense Advanced Research Projects Agency (DARPA) and the United States Army have teamed to develop and field an advanced warfighting capability called the Future Combat System (FCS). FCS is defined for the Army by its Training and Doctrine Command (TRADOC) as a ***networked system of systems*** that will serve as a core building block in developing the "overmatching combat power" with agility and versatility within the combat battalion necessary for full spectrum operations.

The FCS will be comprised of a family of advanced, networked ground-based maneuver, maneuver support, and maneuver sustainment systems that is expected to include both manned and unmanned platforms. As detailed in [1] and [2], the FCS will rely on an enhanced suite of information technologies, sensor networks, and battle command systems that will enable the combat battalion to operate at a level of synchronization heretofore unachievable.

FCS is likely to consist of a family of innovative new platforms, the largest of which will be far lighter than current mechanized armored systems, with each element possessing a common suite of characteristics with respect to mobility, survivability, and sustainability. Some FCS platforms will be multifunctional and modular, combining two or more battlefield functions such as assault fire, indirect fire, point air defense, network communications, battle command, mobility support, and Intelligence, Surveillance and Reconnaissance (ISR). Other platforms, such as small, unmanned aerial and ground vehicles, may be single function.

The FCS will enable soldiers to fight as teams with a high level of synergy and force effectiveness and support all forms of ground and vertical maneuver. It will also provide the means for maneuver forces to generate organic

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complementary and reinforcing effects. The FCS will be able to destroy future advanced targets and combat systems from distances of zero meters to ranges beyond the horizon. To achieve the required level of survivability, these FCS forces will require an unconventional seamless C^4ISR network, capable of ensuring survivability through information dominance, unmatched flexibility, mobility, and extended reach. The result will be that the Future Combat System will provide its force with the same level of confidence that current soldiers have in today's armored heavy force systems. With integrated tactical and operational ISR capability and configurable communications networks reaching from nation/strategic to the individual soldier system, the FCS will enable improved situational understanding to allow FCS units to see first, understand first, act first and finish decisively.

In summary, the FCS is not expected to be a single entity but, more likely, ***a networked system of systems*** manned by soldiers, and supported by both manned and unmanned fighting units that significantly enhance overall force effectiveness beyond that which is achievable today with stand alone and non-networked ground combat systems. In order to achieve this revolutionary improvement in combat effectiveness, it is also recognized that the FCS will require significant advances in communications to seamlessly integrate the Command, Control, Computers, and Communications (C^4) and Intelligence, Surveillance and Reconnaissance (ISR) components into a distributed, mobile fighting force with "overmatching combat power" and sustainability, agility, and versatility necessary for full spectrum military operations in the decades ahead.

For the last two years, DARPA's Advanced Technology Office has been conducting a series of technology development efforts intended to demonstrate the feasibility of achieving such an advanced networking capability on the future battlefield. The purpose of this paper is to explain the motivation for, and summarize the communications technology developments under, this DARPA FCS Communications program [3, 4].

1.1 Motivation

Communications among ground mobile elements requires increasing amounts of RF spectrum to support the increasing requirement to rapidly and efficiently exchange information. In the traditional military communication bands (i.e. VHF and UHF) there is insufficient spectrum available to achieve the required orders of magnitude improvement in data rates over conventional systems. This creates a major new technology objective; spectrum availability.

At the same time, the electromagnetic attacks envisioned against these systems place further increasing demand on the spectrum; Low Probability of Detection (LPD)/ Low Probability of Intercept (LPI) and Anti-Jam (A/J) performance generally require significant additional bandwidth. In the frequency bands generally used for tactical mobile operations (30-2500 MHz), there is generally not adequate bandwidth available to provide both increased capacity and AJ/LPD. As a result, at the onset of this new DARPA program, it was concluded that a "high band" RF system, one operating above the microwave band, would be required to supplement the lower band RF systems traditionally used for tactical operations. Furthermore, since the size of the antenna structures for FCS platforms will be restricted by both their smaller platform dimensions and their required mobility, the selection of the frequency of the high band system became a critical decision (trading antenna gain, propagation characteristics, technology maturity, and spectrum availability). It was concluded that the selection of a frequency band around 38 GHz would enable the simultaneous achievement of high data rates, LPD, A/J, and mobile operation through the use of highly directional antennas. A low band system would still be necessary for interoperability with conventional ground forces, and for operation in environments where a direct line of sight may be unavailable due to terrain, foliage, or weather. However, it was a premise of the FCS Communications program that a moderate degree of antenna directionality would still be mandatory, even for the low band system, to achieve the desired system capacity and AJ/LPD performance. In addition, multiple antenna elements would enable advanced signal processing techniques.

It was recognized at the beginning of the FCS Communications (FCS-C) program that the use of directive antennas required a critical paradigm shift at the network and channel access layers, since most previous work in mobile ad hoc networking had assumed the use of omni directional antennas. Significant innovation in channel access, routing, link establishment, and network adaptivity in response to dynamics would all be required. In addition, to support the varying types of traffic envisioned, the goal would be to support a dynamic mix of real-time and non real-time traffic on a single network.

As a result, innovative mobile ad-hoc networking (MANET) protocols would be required to exploit the robustness and link budget advantages of directional antennas by providing higher capacity mobile adhoc networks capable of operating in a volatile, dynamic, ground mobile communications network. As a result, one of the principle goals of the FCS-C program became the objective of demonstrating enhanced MANET protocols using directional antennas in a dual band networked system operating at both high and low frequency bands. In addition, the program is pursuing development of high band component technology for exploiting microwave-wave and higher (i.e. 35-40 GHz) frequencies, low band (20 MHz to 3 GHz) subsystem technology, RF information assurance techniques, and beam-steered, agile antennas for both high and low bands.

1.2 Critical Observations/Assumptions

Several underlying observations must be made about the Army's Transformation process which directly affect FCS Communications. These are presented to aid in understanding the overall environment for the Army's Transformation:

1.2.1 Heterogeneity and Internet Technology

The communications required to satisfy the multidimensional requirements of FCS will not come from one place; one size clearly will not fit all. Based on the Army's acquisition system, on the character and nature of technology development contributing to the FCS, and on the wide range and complexity of emerging tactical systems only now being developed or fielded, one assumption appears inarguable; that FCS-C will consist of a ***heterogeneous mix*** of numerous technologies and systems, some developed for unique operational communities, and some to support distinct needlines or even unique platforms; but all, nevertheless, different. This heterogeneous character was one of the original catalysts for the Internet, and one of the reasons that it has been recognized for several years that an "***Internet architecture*"**, modeled directly after the civilian Internet and using the same constituent information technology, protocols, and technical architecture as the Internet and Worldwide Web, was the right long term target for DoD and its Global Information Grid (GIG) architecture. This same structure is likely to allow a variety of heterogeneous communications systems to be integrated into the overall FCS "system of systems", including legacy systems, special systems for dismounted soldiers [5], and unique systems for unattended miniature sensors and munition systems [6]. This is an important observation about the resulting Internet structure; it will have to consist of multiple sizes and types of communications systems.

It is, therefore, taken as a "given" that the right approach for the FCS-C system is to apply the same Internet concepts and technology to interconnect the numerous heterogeneous communications technologies yet to be developed over the next decade. In addition, rather than defining an architecture around a specific current incarnation of IP technology (e.g. IP v.6), it is recognized that the Internet and its constituent technology will continue to evolve rapidly, and it will be critical for DoD to be able to evolve with it. Accordingly, it is assumed, therefore, that the ("Big"[3]) FCS Communications System will be an Internet, based on the same underlying IP technology in use in the commercial world, and evolving just as quickly as the civilian and DoD world can propel it. An important element of this evolving Internet will be the autoconfiguration, ad-hoc routing, and host and router mobility management protocols emerging from some of the IP based technology research and development currently under way as part of related DARPA and Army programs [7]. Similarly, the same underlying Internet philosophy will have to effectively integrate a wide variety of communications systems currently being developed by DARPA and the Army for sensor and dismounted soldiers.

1.2.2 Evolutionary Transformation

Driven also by the realities of the Army's acquisition system and by its complex PEO/PM structure, it is also taken as a "given" that FCS will need to be ***evolutionary*** in nature, evolving gradually from the legacy systems in use today as well as the new systems currently being fielded. While this is not to say that revolutionary new capabilities won't be

[3] DARPA terminology for the FCS Force Level communications system

needed, it does establish an underlying framework for the technical solutions developed and the overall environment for their integration into a battlefield of ever-increasing dynamics, dimension and complexity. Therefore, while both the FCS and the Army's Transformation process itself are often presented as a "clean sheet of paper", acquisition and budgetary realities will mandate that many of today's systems will continue to play important roles in the transformation. For this reason, the Interim Brigade Combat Team (I-BCT), constituent legacy systems like the Tactical Internet, and evolving new systems such as EHF and Ka band MILSATCOM, WIN-T, JTRS Wideband Network Waveform, and ABCS (versions beyond v 7.0) will all play important roles in defining the baseline communications environment for FCS. It must be understood that many of these systems, while evolutionary versions of today's legacy systems, must also be considered as important enablers for the future Objective system. In other words, the complete Future Combat System will consist of many technologies beyond those being developed under DARPA's FCS-C program.

1.2.3 Joint Tactical Radio System (JTRS)

The continued development and availability of a software defined family of radios, based on a common open architectural framework and a family of platform-interchangeable waveform software "applications" is proposed as an important enabler for many of the technological elements of the FCS. Accordingly, programs like ACN[4], FCS-C, CECOM's MOSAIC ATD[5], and SUO SAS[6] all must maintain their vision of a ***family of JTRS target platforms***, and continue the development of more than just the set of necessary interchangeable legacy waveforms, but also the development and implementation of a family of ***new enabling wideband multiple access waveforms*** designed for specific JTRS applications (e.g. airborne advantaged nodes). In addition, ***dynamic spectrum management,*** enabled by a software defined JTRS, must be vigorously embraced and developed by the Services and DARPA. It is believed that this area of multiple access and dynamic spectrum management and re-use will be enabled by the software defined radio hardware base developed for both the commercial and military sectors, but also by the continually increasing demands for a limited frequency spectrum. New initiatives in this area need to be pursued by DARPA and the services, working along with responsible Government organizations such as JSC, OSAM, FCC, NTIA, etc. This is noted as an important growth area which needs to be developed.

2. NOTIONAL FCS UNIT CELL DEPLOYMENT

The basic operational requirements for FCS were initially driven by an assumed underlying unit organizational structure represented in Figure 1 below. Notional FCS unit cells, consisting of nominally a dozen platforms, were envisioned to conduct operations over an extended 10 x 25 km area of operations, dependent, of course, on METT-TC[7] constraints. As a result, it was expected that the density of FCS nodes would be markedly lower than for traditional Digitized Forces. This introduces a critical underlying question; will the FCS force have adequate density to support mobile wireless adhoc networks in complex terrains?

2.1 Connectivity in the Ground Environment

In a series of separate analyses, MITRE [8,9] has shown that FCS Communications, the enabler for FCS at large, is likely to be critically dependent on use of airborne (and space-borne) assets due to limited LOS connectivity in complex terrain and foliage. Even after more careful attention is paid to the directional antenna patterns and the RF link budgets for specific radios (at all frequencies), we are confident that terrestrial communications alone will not be adequate to support FCS; airborne and SATCOM networks will have to become critical parts of the FCS system, rather than "opportunistic luxuries". While the foliage modeling for these early analyses was relatively simplistic and probably not entirely accurate, we also believe the results are representative of what more detailed analyses will reveal.

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[4] DARPA's Adaptive C4ISR Node (ACN) program
[5] US Army CECOM's "Multifunctional On-the-move Secure Adaptive Integrated Communications (MOSAIC)" Advanced Technology Demonstration
[6] DARPA's Small Unit Operation Situation Awareness System (SUO SAS) program
[7] Military Environment Descriptor including Mission, Terrain, Time, Weather, Enemy, Troops, and Civilians

Furthermore, we conclude that FCS-C networks will require an architecture utilizing these airborne and SATCOM assets as members of the network (i.e. network routing nodes), rather than simple traditional “relays of opportunity” or range extension supplements; we conclude that these airborne ad-hoc networks will need to be the heart of the FCS-C system, rather than “nice-to-haves”.

Our initial analyses only begin to illustrate the importance of ensuring adequate airborne coverage over the area of operations. Because of the sporadic, volatile nature of assuring continuous airborne visibility from mobile ground nodes, contention for the limited capacity of airborne nodes, and inherent vulnerability

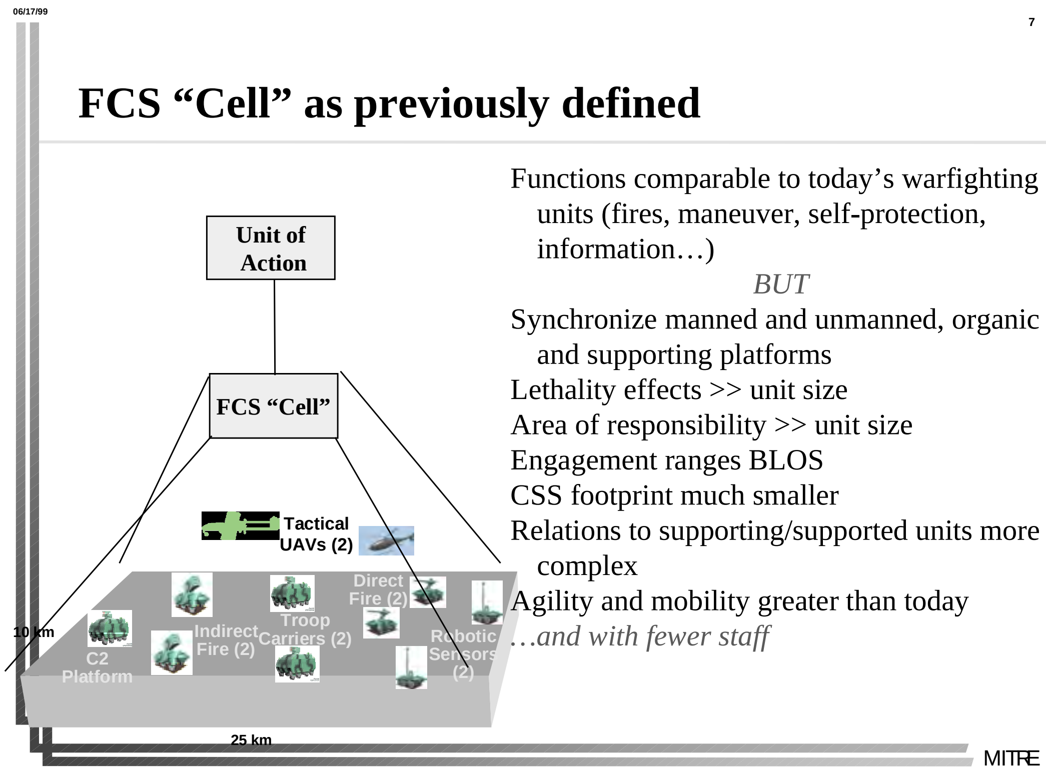

Figure 1 Notional FCS Unit Cell

associated with single points of failure, we expect our continued analysis to reveal quite clearly that an adequate level of coverage can not be reliably provided by a single airborne UAV communications node, as many of the FCS deployments illustrate. Based on this continuing analysis, and under the assumptions of irregular terrain, heavy foliage, and the anticipated sparse deployment density described earlier, we strongly recommend that FCS consider a hierarchical multi-layer network in which the airborne layer consists of an adequate number of airborne nodes, networked together in an ad-hoc fashion using high capacity directional links, and, together, providing an acceptable continuity of coverage over the area of operations. While this certainly needs further examination and continued discussion, we expect our continued analysis to reveal that the number of required airborne nodes will be more than one, and perhaps as high as three or four available to each FCS unit cell. While this doesn't imply that these airborne assets must be assigned to the units below them on a dedicated one-to-one basis, it does imply a reasonable density of airborne nodes at varying altitudes and elevation angles, for both continuity of coverage, for adequate survivability, and for efficient channel access and resulting capacity delivered to the FCS subscriber nodes below. This will assuredly remain a major challenge of the FCS program. We are looking forward to extending this analysis to examine potential elevation angles and blockages due to terrain and foliage in realistic FCS deployments.

3. TECHNOLOGY BEING DEVELOPED

As part of DARPA's FCS-C technology development [3], the following sections summarize the technology components being funded. In some cases, technical material provided by each of the Principal Investigators was utilized to develop this section.

3.1 Low Band

3.1.1 OFDM Digital Receiver Architecture (Rockwell-Collins)

Rockwell-Collins is developing a multi-carrier modulation (MCM) technique [10] for a JTRS compliant platform to support FCS communications at frequencies below 1 GHz. These frequency bands are of particular importance to FCS due to preferable propagation in complex (urban and foliage) terrain environments. While conventional MCM systems, such as orthogonal frequency division multiplexing (OFDM) provide high data rates in the presence of severe frequency-selective fading channels, Rockwell is concerned that these communication waveforms are unsuitable for FCS due to jamming susceptibility and ease of detection. Accordingly, they have proposed a system utilizing hybrid techniques with frequency hopping (FH) and direct sequence spread spectrum modulation, coupled with MCM, to provide a system that is both AJ/LPD capable and resistant to severe channel distortion from multipath propagation. They are developing a multiple mode packet architecture that provides varying data rates, AJ / LPD, and multipath protection dependent on mission objectives, jamming and channel conditions.

In traditional OFDM systems, a fixed guard time is used to protect against multipath inter-symbol interference. Since FCS may be fielded in terrains where multipath delay spreads can vary over a large range, they include an important capability to adaptively change the guard time based on real time channel measurements. This method avoids burdening the network with unnecessary guard time overhead in situations where it might not be needed.

3.1.2 Adaptive Vector Orthogonal Frequency Division Multiplex (OFDM) Waveform (Raytheon)

Raytheon [11] is developing a hybrid FDMA/CDMA/TDMA technique called Adaptive Vector Orthogonal Frequency Division Multiplex (AV-OFDM) that offers the advantages of each of these techniques, plus a frequency hopping (FH) mode. The basic waveform has already been demonstrated to be exceptionally effective in multipath and interference environments, and against feature detectors. The AV-OFDM extensions of this adaptive waveform will provide the greater range of adaptation needed by FCS.

AV-OFDM provides long-range link closures in restrictive terrain, while simultaneously providing highly covert LPD and jam resistant performance. Its flexibility includes a wide range of self-adaptive data rates and corresponding processing gains. Most importantly, it provides spectral tailoring to meet virtually any frequency allocation constraints, a fast frequency hopping mode for enhanced AJ performance, and dynamic digital beam and null forming to minimize the effects of jamming and detectors while enabling frequency re-use.

3.1.3 Low Band Radio Subsystem (Raytheon)

A low band communications subsystem is central to supporting the necessary information exchange requirements to support FCS objectives of lethality, mobility, supportability and survivability. The low band system will be required to maintain assured communications with multiple platforms through various complex terrains and foliage, as well as inclement weather in a dynamic theatre. The requirements for the low band radio links include[8] those shown in the following table:

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[8] FCS Communications technology program BAA 01-01

Data Rate	High throughput	10 Mbps
	LPD mode	200 kbps
Jamming Rejection	Spatial 45°	> 10 dB
	Temporal	> 40 dB
Latency	< 200 ms roundtrip	
Node Entry	< 10 seconds	

Table 1 FCS Low Band Radio Requirements

Raytheon's candidate low band radio is an adaptive, software-defined, scalable radio providing assured communications as shown in Table 1 under essentially all environments, threat and mission conditions, for the 20-3000 MHz frequency band. Each node in the low band system will be capable of satisfying competing demands for LPD/AJ, high data rates, RF propagation, security and primary energy source conservation. This will be achieved by using UltraComm radio modules hosting a revolutionary adaptive waveform, integrated with adaptive, directional beam-forming antenna technology. Through software download, the UltraComm modem may also use other specific waveforms, including a Titan Corporation "Gaussianizer" module, which contains the added logic used to provide a featureless LPI/LPD cover, first used in the SUO-SAS program.

The dynamic nature of the FCS Communications problem space demands an embedded software-radio architecture with multiple self-adaptive elements and an integrated intelligent "engine" to arbitrate conflicts, smooth/adapt incompatible response times, initialize, synchronize, and manage system resources. Raytheon's approach builds on selected critical enabling concepts from the JTRS program. They are adopting the JTRS SCA, using commercial operating systems, design languages, and source languages throughout.

To meet the requirements of the FCS-C program, Raytheon is extending the current capabilities of their UltraComm radio to meet the communications requirements detailed in Table 1.

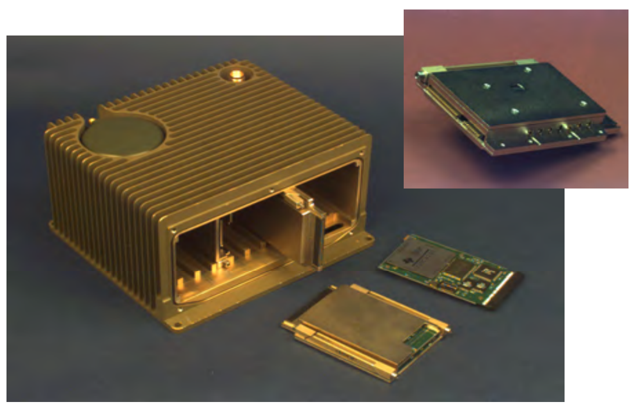

Figure 2 UltraComm PCMCIA Cards in ARMS chassis

The current version of UltraComm is a PCMCIA based system of cards, including RF Receiver, Transmitter, Power Amplifier, Modem, Up/Down Converters and Infosec modules that fit into a scalable Advanced Remote Multifunction System (ARMS) chassis, shown in Figure 2. UltraComm [12,13] combines multiple layers of revolutionary technology, including RF MEMS filters, and SiGe ASICs. The result is that the current UltraComm achieves a revolutionary reduction in size weight and power over existing military radio systems. However, since the current UltraComm modem does not have the processing capacity to handle the highly complex, high data rate, spread spectrum waveform required for assured FCS communications, Raytheon is enhancing the processing capability to be capable of performing narrowband and very wideband (25 MHz) operations and high data rate throughput. This modem is being developed using the highest performance commercial Digital Signal Processors (DSP), Field Programmable Gate Arrays (FPGA's), and Analog to Digital converter (ADC).

3.1.4 Low Band Antenna System (BAE Systems)

BAE Systems is developing an RF and antenna architecture that will be able to demonstrate directional networked communications for the Low Band portion of the FCS-Communications program. BAE Systems has built an antenna array using their patented Meanderline Loaded Antenna (MLA) technology which covers 30 MHz through 2400 MHz in three sub-bands. An antenna controller has also been designed that can simultaneously steer up to two low band beams and one null in any direction within 5 microseconds using these antennas.

MLA antennas continuously cover the 30-2400 MHz band through three sub-bands: 30-150, 150-600, and 600-2400 MHz. There is no tuning of the antenna, which means that the entire frequency range is available at any time. Future communications will require both omni directional and directional capabilities, and these are best satisfied by a circular array. BAE Systems has built such a circular array composed of six antenna elements in each of the three sub-bands. This array is used to create both the omni and directional patterns required for FCS Low Band Communications.

The antenna controller provides amplitude and phase excitations to each antenna element. These excitations can provide, for each frequency, either an omni pattern, or a single beam with an independently steerable null, or two independent beams with an independently steerable null. The controller can change states between omni and directional, and change the beam and null positions within 5 microseconds. The antenna controller is an active device providing amplification to compensate for beamformer losses.

The result of this program is a FCS Low Band Antenna architecture that provides superior gain performance to conventional omni systems. The capability to supply independently steerable beams and nulls allows the demonstration of an LPI and Jam-resistant communications system below 2000 MHz.

3.1.5 UHF Antenna Array over High Impedance Surfaces (Titan)

Under the DARPA RECAP ARCHES program, Titan has developed a technology known as Artificial Magnetic Conductor (AMC) which provides a high impedance surface for paste-on low profile low band antenna arrays suitable for a wide variety of platform surfaces. The basic elements are capable of providing modest (4 dBi) antenna gains, with multiple elements easily combined into effective higher gain arrays.

Under the DARPA FCS-C program, Titan is applying the AMC technology to a variety of candidate designs for conformal broadband low band antennas. The advantage of these structures is that they have good horizon gain and are well suited to a variety of mounting configurations on small platforms. While the behavior of planar wire antennas over AMCs is well understood, they are not suitable for top mounting on platforms. As a result, Titan is applying an innovative planar slot element over the AMC, with the objective of finding a design suitable for side or top mounting and vastly improved FCS platform integration properties.

The resulting AMC backed elements are expected to meet the FCS requirements for low band antenna gain in a compact, light-weight, low profile array package. Instead of attempting full bandwidth solutions, Titan has resorted to a lighter weight, tunable approach using varactor diode tuning to cover 25 MHz bandwidth on any selected band. Their elements have evolved to “bowtie” slots as opposed to wire elements originally considered, integrating better into the structure.

The current technology development effort will conclude with a two element sparse array. It is anticipated that the weight and form factor for a low profile tunable (25 MHz instantaneous bandwidth) UHF (225-450 MHz) element would be 16”x16”x1.35”, and weighing approximately 5 lbs.

3.1.6 Bell Labs Layered Space Time Processing (BLAST) for FCS Communications (Lucent)

For the past few years, Lucent (Bell Labs) has been experimenting [14,15,16] with a technique known as Bell Labs Layered Space Time Processing (BLAST) as a mechanism for enhancing spectral efficiency by capitalizing on the inherent spatial diversity from multiple antenna elements in multipath channels. BLAST is a space-time signal processing technique which constructively uses multipath, created naturally in most ground mobile environments, and received via multiple antenna elements, to set up multiple independent parallel channels at the same frequency. It transmits and combines the multipath arrivals (transmitted and received by multiple antenna elements), providing significant coherent gains even in strongly scattered environments, as well as significant diversity benefit against multipath fading. The indirect potential benefits of this technique, particularly for FCS applications, are the high spectral efficiency, high AJ against broadband jammers, lower symbol rates for improved LPD and, accordingly, higher spreading factors achievable in a given bandwidth. The objective of the DARPA funded effort is to integrate BLAST with adaptive arrays for spatial nulling against broadband interferors, plus to validate the effectiveness of the technique in ground mobile applications in cluttered, obstructed terrains including foliage.

As part of this effort, Lucent will be conducting propagation experiments to evaluate these combined techniques under conditions of ground foliage. The key issue under examination is whether or not the local scattering due to foliage can be effectively exploited, and to characterize the impact of the scattering on the spatial nulling of jammers.

BLAST is complementary to antenna beamforming, and hopefully will offer the potential for being integrated into low band FCS-C systems.

3. 1.7 Microswitched Reconfigurable Aperture Development (GTRI)

As part of the DARPA RECAP program, GTRI has been exploring innovative ways of controlling the conducting antenna elements used for low band array structures with electrically small conducting pads and FET switches. They are striving for single element coverage of the 800 MHz to 2 GHz band and have completed predictions of acceptable beam reconfiguration over a 60 degree angle with ground planes at L-Band (1-2 GHz). Current technology challenges include the switch capacitance which tends to prevent operation above 1.8 GHz and the feasible pad density which tends to limit overall performance. They are also experimenting with resistive grid lines which eliminates the requirement for any hardware on the aperture itself. Their objective system design would use a small chip containing all FET circuitry for the switching element, capable of supporting a good portion of the FCS-C low band requirement.

3.2 High Band

3.2.1 Wideband Millimeter Wave Radio (TRW)

One of the key goals of the FCS Communication program has been to demonstrate the viability of high band (35-40 GHz) radios in supporting a wideband mobile adhoc network in tactical battlefield environments. The central focus of this issue has been the feasibility of using MMW radios in cluttered, obscured environments typified by terrain, foliage, smoke and dust. It is the intent of the DARPA program in this area to demonstrate that 38 GHz radios can effectively be used in such applications while providing the required capacity, AJ/LPD, and mobility to support FCS units.

TRW’s goal in this effort has been to design and fabricate a technology baseline which could be inserted in later stages of the FCS program as a common high band network element. TRW’s goals in this phase of the program have been to demonstrate mobile adhoc networking using 38 GHz radios, with multiple simultaneous directional antenna beams providing improved performance over omnidirectional beams, and with electronically reconfigurable antenna apertures to support the necessary network functionality and mobility.

TRW’s underlying technologies for this phase are based on two different commercial products, one a 38 GHz trunking transceiver developed by TRW for Nokia, and the other, a TRW/L3 Wireless DSL modem and 5.8 GHz transceiver.

The performance goals in this phase are to demonstrate peer-to-peer performance at data rates exceeding 100 Mbps, and ranges exceeding 13 km, in ground-air and ground-ground applications within an FCS Unit Cell. Testing and demonstrations are planned for both foliage-obscured and mobile scenarios, as well as with ground and airborne nodes.

The demonstration radio will initially use fixed sector horn antennas at 38 GHz, and multiple MMW transceivers per platform. The radio is based on an FPGA modem and MMIC transceiver that supports a CDMA/TDD/QPSK/FM waveform. A data rate of 32.5 Mbps has been demonstrated at ranges of up to 5 Km at 38 GHz, along with mobility up to 45 miles per hour.

The objective high band system proposed by TRW will use multiple transceivers, multiple sectors of reconfigurable array antennas, and will operate at data rates of up to 128 Mbps, using 4 W of transmit power and channel bandwidths of 200 MHz in the 35-40 GHz band.

3.2.2 High Efficiency High Band Transmitters (BAE Systems)

One of the technology barriers in this phase of the FCS-C program has been the availability of affordable, high-efficiency high band transistor power amplifier MMICs. BAE Systems' objective in this program has been to demonstrate the performance achievable at 38 GHz using metamorphic HEMTs, or MHEMTs, which consist of InP HEMTs produced on GaAs substrates for high performance with low cost. As described in [17], MHEMT devices offer significant potential for reduced DC power consumption (10 dB gain per mW at X-band), high gain per stage, the lowest noise figures of any technology, and ultra-wide bandwidths (100's of GHz). Although PHEMT MMICs are fairly well accepted for commercial Ka band applications, they have been limited to 1 or 2 W maximum power with low efficiency, and MHEMTs promise further improvements in prime power requirements (efficiency), power output (4W needed), thermal load, and cost.

BAE has developed initial MHEMT MMIC designs for 100 mW, 1W, and 4 W output power, capable of high gains (15-20 dB) with wide instantaneous bandwidths (4 GHz). An initial MMIC fabrication run is underway, with completion and test results expected by April. Future activity would include integration into a 4W demonstration module, a second MMIC cycle to refine performance and scaling of the MMICs to larger wafers (6-inch) for reduced cost.

3.2.3 High Band Antennas (BAE Systems)

One of the important requirements of FCS Communications is the availability of affordable, electronically steered, 38 GHz array antennas. The cost driver for conventional phased arrays is the number of elements because each element is fed by its own electronics module. The BAE Systems approach is to use travelling wave arrays that are fed at only one end. These N-element linear arrays are then arrayed to create a planar two-dimensional NxN array. There are N modules feeding each linear array. The potential for cost savings is tremendous because the cost is driven by a factor of N rather than N squared where N is the number of elements in a square array.

BAE is building one of these prototypes, using a unique combination of technologies, namely Variable Impedance Transmission Line (VITL) with piezoelectric control. The VITL transmission line changes its propagation constant based on the mechanical spacing between the ground plane and transmission line. This spacing is controlled through a piezoelectric actuator. The radiating elements are electromagnetically coupled dipole antennas.

Under this phase of the program, BAE has demonstrated a prototype single linear scanning VITL array with beam positions from –10° through +40° from boresight. Simple shims were used to change the ground plane spacing for this VITL array, but electronic control through a piezoelectric actuator is the next step in development of this technology along with arraying these antennas in two dimensions.

3.2.4 P-MEMS 2D Scanned Surface Technology Antenna (Ball)

With a diverse background in antenna technology and ongoing support to the DARPA RECAP program, Ball Aerospace & Technologies Group is developing a technology which has a potential of providing low cost phased arrays for the FCS-C high band subsystem. The technology uses an active Polyimide MEMS switched conformal lens, consisting of a MEMS-switched active lens constructed on top of a passive feed network, the combination providing a

+/- 45 degree adjustment in beam direction in two dimensions. In order to simplify the structure, one dimensional hybrids are also being considered which require some other means of beam steering, such as mechanical gimbals or phased arrays structures. These lens panels can be configured as flat panels or multi-sided polygons to provide multiple sectors of coverage. As such, they offer the potential of conformal structures for a variety of platforms. The advantage of this construction is light weight and low cost, bulk fabrication (since it uses PC card processes), and a reduced number (M+N) of connections for beam steering control. The technical challenges include reducing insertion loss and phase delay with a minimum number of extra components.

3.2.5 High Band Directional Beamforming Array (Rockwell-Collins)

Low cost and low antenna profile requirements are key system drivers for the high band FCS-C system. Accordingly, Rockwell-Collins is developing a high band (35 GHz) solid state electronic beamforming antenna prototype capable of supporting high data rates and AJ/LPD. An initial system design has been developed, beamforming algorithms selected, block diagrams completed, and hardware/software design is in process.

The prototype being built [18] uses a baseband receiver/exciter operating at 5.8 GHz, taken from an Enhanced Wireless LAN program at CECOM, along with a 38 GHz up/down converter. Phase shifters and quasi-optic power amplifiers for a 38 GHz design have been fabricated and are under test, and a prototype 1 x 4 element demonstration antenna array is being planned. Objective system design would require a multi-face structure consisting of 30 x 30 element arrays on each face. The figure below shows the objective system design for the Rockwell multi-face 38 GHz beamforming array structure.

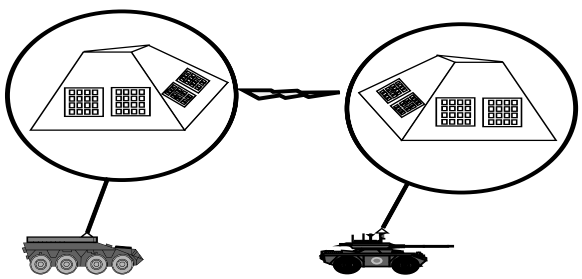

Figure 3 Rockwell Objective High Band Beamforming Array

3.2.6 Low Cost RF Lightwave Circuit for Low Phase Noise MMW sources (Ipitek)

Since phase noise in the front end components limits the performance of all radio communications systems, and phase noise problems increase with higher RF and local oscillator frequencies, Ipitek has proposed to apply light wave (photonic) techniques to meet the need of FCS Communications for low phase noise MMW sources. As part of the DARPA technology program, Ipitek is developing a 38 GHz photonic tone generator and PSK transmitter. This technology offers a single chip integrated approach to optical processing and brings significant savings in power drain, size, and weight, while eliminating the vibration susceptibility and noise of conventional sources for high band communications systems. These devices eliminate the MMW sources required for high band transmitters and replace them with small laser-generated signal sources with excellent phase properties. Lithium Niobate (COTS) optical modulators replace the normal modulators, upconverters and millimeter wave local oscillator, fiber optic filters replace RF front end components, and lossless optical cabling simplifies antenna remoting.

3.2.7 High Capacity LPD Technology (HILT) (General Dynamics)

One of the important baseline objectives of FCS-C is to demonstrate high levels of AJ/LPD in both high and low band waveforms. One aspect to this solution is, of course, the use of narrow beam, high gain directional antennas. The other dimension of the problem is in the basic waveform design.

Under DARPA funding, General Dynamics (previously Motorola) is developing an extremely wide bandwidth (>100 MHz) featureless spread spectrum waveform capable of providing over 40 dB of narrowband interference rejection, and scalable in processing gain vs data rate over 10's of dB. They have designed a high performance DSP modem capable of supporting the estimated transmitter requirements of 4.2 GFLOPS and receiver requirements of 12.5 GFLOPS. They envision operation at carrier frequencies of 100 MHz to 94 GHz and, therefore, potentially support both high and low band FCS-C systems. Initial work is limited by performance of the underlying COTS DSP technology, and will deliver lower processing gains (10 dB) at low band (160 MHz) in the initial stages, to be followed by higher processing gains (20 dB) at high band (38 GHz) by the end of this phase of the program.

General Dynamics has assembled a HILT waveform development environment based on a Sun Ultra workstation running Solaris and a VME chassis consisting of single board VxWorks computers, Mercury motherboards, and an analog IF transmitter. On the receiver side, a VME chassis contains a similar VxWorks single board computer and four Mercury motherboards containing twelve PowerPC processors and one IF receiver.

3.3 Networking

In [19], the SST established a number of ground rules regarding the networking anticipated for the DARPA FCS-C program[9]. Rather than to define requirements, these were used mainly to stimulate and help focus discussions with contractors working this area:

- **No base stations**. We do not anticipate that the FCS wireless network will consist of either a "cellular" or "hub-and-spoke" architecture configured around base stations. Specifically, we envision an ad-hoc multihop network consisting of both ground and airborne nodes. The main justification for this assumption is the resulting complexity of any cellular or hub/spoke architecture at the central node, compared to that of multi-hop flat (or hierarchical) networks.
- **No specific hierarchy is assumed for the architecture**. We have not identified a specific hierarchical structure that is believed to be appropriate for either (a) networking within the FCS Cell {the focus of the FCS-C program} or (b) networking among FCS Cells. We expect that the networking technology to be developed under this program will be extendable to include networking among FCS Cells. Ideally, the algorithms that automatically configure the network will need to be resourceful enough to develop the most appropriate connectivity for the existing locations of nodes, blockage conditions, traffic demand, and QoS preferences.
- **Directional Antennas**: Because of the use of directional antennas and the resulting directional confinement of RF radiation (particularly in the high band), we believe that multiple links can coexist simultaneously within the same channel without requiring CDMA. We expect a number of interesting alternative approaches to this unique multiple access challenge to be considered.
- **Protocol Layering**. The FCS Systems Study Team believes that serious attention should be devoted to observing traditional layering of protocol software. We also believe that directional networking begs to admit the transfer of additional forms of data and control across the interfaces between protocol layers. The team recommends that the FCS-C contractors adopt a common standard for the interface specification and implementation.
- **Common Link API.** Here we define the Link API to be the software primitives (procedures and procedure calls) that enable the transfer of information and control across the interface between the network and link layers (layers 3 and 2, respectively). We recommend that the contractors adopt a common API.
- **Network Security.** Security must be considered in the design of the network architecture, protocol layering, and network interfaces. While it is not expected that the implementations under this effort will be fully secure, we do expect that effort will be taken by the FCS-C System Integration and Demonstration contractors to achieve a flexible implementation that will admit the insertion of software and hardware security modules at multiple protocol layers.

In response to this guidance and the DARPA Broad Area Announcement [3], two contracts were awarded to pursue the development of MANET protocols capable of exploiting directional antennas for improvements in AJ, LPD, and network performance. These network efforts are summarized in the following section:

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[9] Networking contributions were from FCS Communications SST members at NRL, MITRE, and CenGen.

3.3.1 Utilizing Directional Antennas for Adhoc Networking (UDAAN) (BBN)

As an extension of earlier work done on a number of DARPA programs, BBN has undertaken the design and demonstration of a family of ad hoc networking protocols that both support and exploit directional antennas [20-24]. Their contention is that the directionality inherent in high gain antennas can significantly improve the performance of ad hoc networks by delivering higher effective capacity, lower latency, robust connectivity, and enhanced security. They plan to develop these protocols and implement a portable software system that can be readily integrated into high and low band FCS-C systems.

Based on a contention based channel access approach, BBN's UDAAN [22,23] applies a number of innovations at the MAC and network layers to achieve demonstrable improvement in spatial reuse and network connectivity. To assist in transitioning their protocols to actual hardware, they have embraced a recommended set of standard APIs for transceiver and link interfaces within the system. Software will be delivered under this phase of the program in portable form (initially targeted for Linux platforms), along with simulation models in OPNET/QUALNET.

The following table summarizes the functionality expected in the completed suite of UDAAN protocols over the life of the current DARPA program.

Key Basic UDAAN Functionality	**Key Enhanced UDAAN Functionality**
Unicast routing, 3 metrics + min-hop	**Multicast routing**
Informed neighbor discovery	**Blind neighbor discovery**
	LPD neighbor discovery
	Security (Authentication, jammer null)
Link metrics	**Node metrics**
"Back-door" position information	**Position information module**
Directional MAC	**Power control, dual channel priority MAC**

For channel access (link layer), UDAAN uses a directional MAC based on "unscheduled access" (CSMA/CA), in which RTS/ CTS, DATA and ACK are all sent directionally, with directional carrier sense used to further avoid collisions. The UDAAN MAC provides the ability to use separate control channels for RTS/CTS exchanges, as well as the ability to use multiple data/acks per RTS/CTS to reduce handshake overhead. As initially demonstrated under the GloMo program with DAWN, transmit power control is also effectively used to optimize spatial reuse [21].

For the network layer, UDAAN uses a "Hazy-sighted Link State" routing protocol which was also initially developed under the DARPA GloMo DAWN program [22], with which each radio builds and distributes next-hop tables for forwarding, based on destination and quality-of-service requirements from higher layers.

Neighbor discovery is based on link establishment with as many nodes as possible, where discovery is uniquely adapted to antenna/radio capabilities. In this area, BBN has developed a fairly complex set of tradeoffs between neighbor discovery efficiency and LPD, and is implementing the protocols in a phased approach with progressively increasing capabilities[24]. Sharing of neighbor information is accomplished across frequency bands (i.e. high/low band) and several techniques are being considered for initial neighbor acquisition, including both blind and informed (i.e. "out of band" aided) techniques.

To support this program, BBN has applied their Portable Switch Framework (PSF) which enables code sharing across both simulation and real-life platforms, reduces porting to writing of a small OSAL for the target system, and has already been demonstrated for OPNET, FreeBSD, Linux, Windows 98.

3.3.2 Bandwidth Efficient Networking (BEN) with Beamforming Antennas (Raytheon)

To meet the FCS-C challenge to improve LPD while maximizing network performance with directional antennas, Raytheon is developing a suite of network protocols called Bandwidth Efficient Networking with Beamforming Antennas (BEN). Their approach [25] exploits the advantages of directional antennas for both transmit and receive, while decreasing the amount of broadcast traffic. A distributed TDMA protocol is utilized to resolve contention while at the same time decreasing control traffic using geographic information. Routing is handled by an exclusionary tree algorithm called Partial Link State Routing (PAL).

Raytheon has assumed an architecture based on a JTRS radio, using both high and low band modems under a suite of MAC and routing protocols. Both high band Receiver Oriented Multiple Access-Directional (ROMA-D) and low band omnidirectional Node Activation Multiple Access (NAMA) MAC protocols feed a common BEN link layer which provides a common single interface to the router. Due to the challenging propagation characteristics expected at high band, Raytheon believes that neighbor discovery will have to rely on low band services before antenna beams can be pointed and high band neighbors can be established. This coupling of the high and low band neighbor discovery process results in a combined link layer which enables them to smooth out some of the dynamics of high band connectivity. NAMA supports both unicast and broadcast services, while ROMA-D is best suited to point-to-point unicast transmissions. Raytheon's channel access and scheduling for NAMA and ROMA are described in detail in [25].

Partial Link State Routing (PAL) is a proactive link state routing protocol based on partial link state information, derived from the STAR protocol developed at U. of California-Santa Cruz by Garcia-Luna-Aceves under an earlier DARPA GloMo effort. It is believed that PAL fits nicely with directional antennas since nodes can send routing updates on a point-to-point basis. In STAR, a node communicates its source tree to all its neighbors whereas in PAL, a node only communicates an exclusionary source tree that does not include the node itself. This enables each node to learn about alternate paths, all with less overhead than STAR required. Routing updates must be reliably exchanged periodically among neighbors.

3.4 Related R&D

3.4.1 K/Ka Band OTM SATCOM (SPAWAR Systems Center San Diego)

Under an independent exploratory development program at SPAWAR Systems Center, San Diego (SSC-SD), the Office of Navy Research (ONR) has been funding the development of high data rate (T1+) K/Ka band (30/20 GHz) mobile SATCOM technology which is believed to be an important element of the future FCS-C system, providing critical reach-back from mobile fighting platforms. The efforts acknowledge the importance of the military's emerging Wideband Gapfiller Satellites (WGS) and AWS as well as various commercial satellites in this important band, and motivated the Navy to help develop a common terminal. After several years of proof-of-concept demonstrations and a competitive procurement, SPAWAR awarded their current contract for the Advanced Ultra Small Aperture Terminal (USAT) in FY 99.

The USAT program includes investment in affordable K/Ka Band GaAs MMIC phased array antennas (Boeing) and miniaturized MMIC frequency converters (Hittite Microwave) which are needed in building full duplex mobile SATCOM terminals for surface ships, aircraft, and ground mobile platforms. Regular updates on the SPAWAR USAT program have been provided at FCS-C PI Meetings [26-29].

3.4.2 High Fidelity Scalable Simulation of FCS Networks (Scalable Network Technologies)

In addition to the challenges of integrating adaptive antennas into mobile ad hoc networks in widely separated frequency bands, a major challenge being addressed is the development of appropriate modeling tools for analysis of the behavior of large scale networks in complex environments. As part of DARPA's FCS-C program, Scalable Network Technologies has been conducting supporting modeling and simulation using QualNet, a commercial derivative of GloMoSim, a product developed under DARPA's earlier GloMo program.

Qualnet is a new generation of efficient, high fidelity modeling and simulation tools that is being used to provide enhanced modeling capability for FCS Communications. It has been interfaced to a variety of Government scenario generators and has extensive integrated analysis facilities. Qualnet was also developed with an integrated GUI for model design, animation, tracing, and statistical analysis and is being used, in addition to OPNET, to model the behavior of FCS-C networks. One such analysis presented in [30] examines the behavior of directional antennas in mobile adhoc networks. Another such recent paper [31] studies a new carrier sensing mechanism called DVCS (Directional Virtual Carrier Sensing) for wireless communication using directional antennas.

3.4.3 Sensor Radios for FCS Communications (US Army Research Lab)

In a supporting R&D program, ARL and CECOM have been developing a networked sensor radio suitable for unmanned ground sensor (UGS) networks, of the type envisioned to be used widely in support of FCS. While not part of the FCS-C networks per se, these UGS networks will provide an important traffic source for FCS Communications, providing significant traffic load that needs to be carried into, and across, FCS-C networks.

The UGS networks themselves have uniquely different operational characteristics, and hence particularly unique design constraints, which differentiate them from any other networks on the battlefield. UGS networks need to be extremely low cost, even expendable; they need extremely low battery drain to support long mission lives; they all have extremely low antennas mounted at, or slightly above, ground level, and they are required to support intra-sensor field communications over short ranges (nominally < 1 km).

Accordingly, ARL is developing a prototype "blue radio" which operates in the tactical UHF band where propagation is fairly tolerable (and a military allocation exists), uses spread spectrum and fast acquisition to provide significant AJ protection, and operates at extremely low power (<600 mW) to achieve long battery lives. The radio is expected to provide data rates of several Kbps. The implementation relies on commercial components driven by the cell phone industry to desirable size, weight, and power, and a DSP radio for flexibility and future growth. Working with contractors from the ARL Collaborative Technology Alliance in Telecommunications, ARL is integrating MANET multihop networking protocols to support the unattended, random deployment envisioned for these devices.

3.4.4 Modeling and Simulation Team (US Army Research Lab)

Realistic operational scenarios and device models must be developed in order to adequately evaluate FCS-C technologies. The reliability of the simulation results is highly dependent upon the level of fidelity (or "realism") to which these scenarios and device models are represented. While the device models will be provided by the contractors, the FCS-C Modeling and Simulation (M&S) team focused on defining how the contractors should develop their device models in order to operate in a government-defined simulation environment.

An FCS-C M&S Plan was developed by the M&S team consisting of ARL, MITRE, Naval Research Labs (NRL), and CECOM and published in [19]. It described the process by which they would provide the contractors with one or more sample FCS operational scenarios with which to test their emerging network system model(s). The FCS operational scenario(s) will be developed jointly by the FCS-C System Study Team and the FCS-C M&S committee. Several alternative forms in which the scenario(s) would be delivered to the contractor(s) were identified and contractor(s) were invited to provide input to the FCS-C M&S Team regarding their preferences, along with supporting justification.

Test scenarios are being developed by MITRE for use by the FCS-C M&S committee and the contractors to analyze system performance, and, thus, determine suitability of the proposed technologies to FCS operational requirements.

The FCS-C M&S process is illustrated in the figure below. The contractor(s) provide prospective device model(s) to the M&S committee. The committee implements the operational scenario(s), quantifies the network performance for each contractor's device, and evaluates the results. Two key components in the FCS-C M&S process are the RF propagation model and the FCS operational scenarios. In order to realistically model the FCS-C network, an accurate RF propagation model is required. The RF model is composed of several pieces that, when aggregated, provide a realistic representation of the channel. Of critical importance are the terrain, foliage and multi-path effects on the physical channel, as well as the modeling of weather and atmospheric absorption effects, as discussed in a later section of this paper.

Unfortunately, as the realism of the propagation model increases, the simulation runtime generally also increases, sometimes dramatically. Because of this, several efforts are underway to improve the RF channel modeling. Initially, the Joint Spectrum Center's TIREM [32] propagation model will be used, along with various emerging foliage supplements, to predict path loss through terrain and foliage. As the research completes, additional modeling tools will be incorporated into the set of simulation tools being used in the FCS-C M&S process.

In order to allow accurate comparisons among contractors, a common set of simulation tools and, perhaps, a simulation environment are required. OPNET Technologies' discrete event simulation tool OPNET will initially be used as the baseline communication and network modeling tool. As such, FCS-C contractors are required to deliver OPNET models for their devices. The M&S committee, however, has also encouraged contractors to develop and utilize QualNet models. The contractor-developed QualNet models were considered optional, and are treated separately from the required OPNET models. Initially, they plan to be used to help determine the scalability of the contractor devices in large networks.

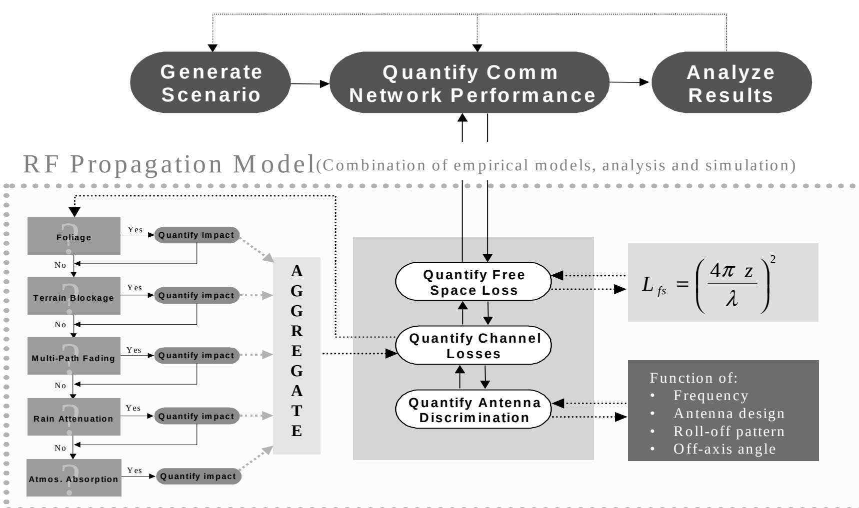

Figure 4 FCS-C M&S Process

3.4.5 Foliage Propagation Research (US Army CECOM Intelligence & Information Warfare Directorate)

An important element of the DARPA FCS-C program is to provide RF propagation modeling and simulation support for FCS communications. Modeling and simulation of wireless networks operating at high band mm-wave frequencies, as well as traditional low band military frequencies (<3GHz) is needed with particular focus on: 1. How to incorporate foliage effects 2. How to determine propagation loss at high band (as extensions to current capabilities, e.g. TIREM), and, 3. How to consider multipath and wideband channel effects at both low band and high band, in all terrains including foliage and urban. Suitable models are needed to address RF propagation between multiple transceivers of a network and operate from a database that is constructed from parametric representation of topographical features, including foliage and urban features. When driven by notional FCS deployment scenarios, this will enable rapid evaluation of candidate FCS networks. To achieve this goal, enhanced higher fidelity RF propagation models are being developed with a physics based approach used to model foliage and asymptotic techniques (ray tracing methods) used to handle multipath effects. Efforts are underway in these areas at CECOM, ARO, ARL, MITRE, U. of Michigan, Pennsylvania State U., and Polytechnic U.

A recent paper [33] reviewed the issues being addressed in research at U. of Michigan and Polytechnic U. for CECOM and ARO. It reviews the utility of the parabolic equation method (PEM) which was developed to account for terrain and gradients of refractive index in the atmosphere, and describes the UTD ray methods developed to account for the effects of buildings and terrain in urban environments. Although progress has been made in the modeling of individual environmental effects, the paper explains that these models have not been integrated into a single tool that can be used for a wide range of environments. The paper concludes by characterizing the plans ahead for integrating the effects of ground foliage on propagation path modeling.

In efforts designed to support the modeling and simulation for FCS-C networks, MITRE has also been integrating the effects of foliage into models of connectivity of adhoc mobile networks deployed in support of emerging FCS scenarios. In this analysis, a number of approaches are being used to address the foliage. One approach was used to simulate the experimental 802.11-based OLSR network deployed in baseline testing to develop the Government's baseline performance criteria for FCS-C networks. That approach [34] models the foliage loss on any foliage obscured paths (at low band) in accordance with Weissberger [35] and computes additional path loss (beyond "smooth earth" or R^4) for any obscured paths, dependent on the amount of foliage penetration. Other approaches apply statistical distributions of foliage height and coverage to estimate the additional path loss beyond that predicted by TIREM on FCS-C networks.

Both of these approaches, including the new theoretical tools emerging from the earlier discussion, are improving the Government's ability to model the performance of candidate FCS-C networks in realistic deployments in ground terrain, foliage, and urban areas.

3.5 Baseline Testing Plan/Status

To facilitate the FCS-C program objectives, the DARPA program plans to conduct a series of three experimental demonstrations, incrementally increasing in both complexity and tactical reality. Two System Integrator (SI) teams [4] were selected to design and demonstrate a system consisting of integrated FCS-C technology components. The performance of the two System Integrators' solutions will be compared to a set of baseline criteria developed by the Government in earlier tests. Successful performance compared to these baseline performance criteria will be a necessary requirement for the SI teams to advance to the next set of demonstrations.

3.5.1 Baseline Test Criteria

To facilitate development of the baseline criteria, the FCS-C Government team completed a baseline experimental field test using commercial-off-the-shelf (COTS) Mobile Ad-hoc Networking (MANET) technologies with omni-directional antennas in October 2001. The purpose of this baseline testing was to collect data regarding the performance of a COTS IEEE 802.11 based omni directional network enhanced by multihop MANET protocols and its ability to support a highly mobile network in complex terrain and foliage.

The test configuration was designed to stress network performance, primarily the ability of the network to respond to high mobility in terms of network changes, exits, and entry (i.e. nodes of the networking entering, exiting, and reforming to achieve network connectivity) in a dynamic network. Spectral (or spatial) reuse, namely the ability to effectively utilize or reuse spectrum by spatial diversity primarily gained via directional antennas, is another critical component of early FCS-C testing. While directional antenna are anticipated to better support spectral reuse, the baseline omni directional antenna demonstration will include it as a component to gather data to compare against a directional antenna based approach in later contractor demonstrations. Baseline performance tests were specifically conceived to highlight and evaluate the spectral reuse achieved through directional antennas and protocols.

3.5.2 Baseline Test Hardware

The FCS-C baseline government test consisted of 20 mobile communications nodes deployed in October/November 2001 in open terrain obstructed by some ground foliage and buildings. The nodes were installed in commercial vehicles rented by CECOM and supported by CECOM drivers. Naval Research Labs (NRL) / CenGen. developed a suite of test hardware and software that was installed and operated in each vehicle. Each vehicle was outfitted with:

- Magnetic roof mount with a 9dBi omni antenna
- Low loss RF cable to connect the 9dBi antenna to a power amp
- 6w RF power amp located inside the vehicle
- SINCGARS battery to power the power amp
- Low loss cable connecting the power amp to a Linux PC which has MANET (multihop) routing[10] software installed
- Linux MANET equipped PC
    - PC also contains application / test software described later
- Orinoco (a.k.a. Wavelan) IEEE 802.11 Gold card
    - Installed in the Linux MANET PC PCMCIA card slot
- Low profile magnetic roof-mount GPS antenna
- Battery powered GPS unit inside the vehicle
    - With RS-232 connection into Linux PC
- Magnetic mount UHF/VHF voice antenna
- UHF/VHF voice transceiver for order-wire communications

The test tool used to generate (and analyze) data flows for evaluating network connectivity was NRL's MGEN/DREC [36]. The tools provide a script driven constant bit rate traffic flow (MGEN) and the ability to receive the flow and graph the received data stream (DREC). The tools were modified to include the GPS location of the source of the data. In addition, a position location tool has been developed to graph, in real time, the location of each node that has network connectivity.

All nodes also executed a position location application (running on the Linux laptop) that is used to generate a small quantity of data containing GPS position reports from each node. This data was transmitted (across the multihop network) to a central command center and graphed in real-time, denoting the position of all nodes that have network connectivity at that instant. It is noted, due to the layout, topography and foliage at the test site, that the nodes often required multiple relays to reach the command center. The network will be evaluated on, among other things, its ability to establish connectivity and deliver position location data at a measurable latency to the command center.

Additional experiments were performed to evaluate spectral (spatial) reuse to be evaluated, anticipating subsequent improvements due to directional antennas used by the two SI teams, in which the ability of the networks to support multiple high rate flows will be evaluated.

In addition to the packet loss, latency, and throughput , Anti-jam and Low Probability of Intercept (LPI) will also be examined in later experiments.

3.6 Prognosis

With the first phase of the FCS-C technology development program nearing completion and the Government's FCS Lead System Integrator contract nearing award, the Army's future directions have yet to be clearly defined. However,

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[10] Optimized Link State Routing (OLSR) software provided by NRL

thanks to the ambitious program goals of DARPA and the significant progress made under the efforts reported herein, the FCS Objective system design should be far more reachable than it might have been only a few years earlier.

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