STATISTICAL ANALYSIS OF DYNAMIC CODING AND MODULATION THEATER LEVEL GAINS

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ABSTRACT

Connecting lower echelons of the force structure to the Global Information Grid, the GIG, is key to the effectiveness of Transformation. This high speed connectivity provides C4I and enables small unit rapid deployment at a Unit of Action (UA) level. The Future Combat Systems program plans to provide over 100 small embedded Communication-on-the-Move (COTM) satellite terminals per Brigade-Level UA. These small terminals will provide T1 (1.5 Mbps) and higher connectivity to UA units. Achieving high speed connectivity will require operation at Ka-band (20/30 GHz) frequencies using Wideband Gapfiller and EHF (22/44 GHz) frequencies using TSAT satellites. This new operating paradigm will require a shift in the way the DoD plans, provisions and operates satellite links. Currently most satellite links are designed for worst case, or near worst case, operating conditions with the modulation and coding chosen to insure link closure between 97% and 99.5% of the time. This results in a substantial waste of link margin and a loss of spectral efficiency since that margin is seldom required. Future MILSATCOM satellites will not have the power or spectrum required to operate thousands of COTM links continuously with very high link margins. Dynamic Coding and Modulation (DCM) has been used in commercial networks to improve spectral efficiency and increase the number of users that can be supported with limited spectrum. DCM achieves this performance by adaptively changing modulation, coding and channel rate as environmental and link conditions changes. This allows RF links to operate with much smaller margins than is possible given static link operations. At lower operating frequencies, such as C-band, typical link margin is small (3 dB) and the advantages of integrating DCM into the architecture is not substantial. But at Ku-band, Ka-band and EHF frequencies the link margin required for acceptable operations can be greater than 10 dB. A number of commercial operators are using advanced DCM coding methods such as DVB-S2 to increase spectral efficiency by 100% to 200%. This paper evaluates the effectiveness of DCM for the MILSATCOM architecture. The authors describe a statistical link simulation model for estimating the advantage of DCM. The model was used to analyze the spectral requirements for a Major Theater of War containing over 1500 terminals. The paper analyzes a Korean theater scenario consisting of 7 FCS Units of Action (UA) and 6 Striker Brigades as well as six UEx units and one UEy unit. The analysis was performed for a regenerative TSAT-like SATCOM architecture using advanced modulation such as 8-PSK and 12-QAM. The paper compares a static link operation to DCM operation and estimates gain in terms of spectral efficiency and transmit/receive burst rate. The results are presented as a function of link margin for a number of deployable Army terminal classes, and as a theater aggregate. For the COTM terminal class, the results show that overall theater uplink spectral efficiency gains of 1.5x to 2x, and average burst rate increase of 2x to 4x are possible in high rain rate regions using DCM versus traditional planning and provisioning approaches.

INTRODUCTION

By using dynamically selected channel rate, forward error correction (FEC) coding and higher ordered modulations, the modern satellite link need not be statically designed for worst case or near worst case conditions. Dynamic Coding and Modulation (DCM) allows advantaged satellite links, i.e., those with excess margin, to operate with higher spectral efficiencies (bps/Hz) or increased burst rates, thus allowing a greater number of users to be accommodated within a prescribed amount of satellite radio spectrum. As RF links experience degradation due to rain fade, foliage blockage or beam pointing errors related, DCM may reduce the modulation order, increase the FEC coding gain, or direct the terminal to operate in a lower baud rate channel (or all of the above if necessary) such that the link is sustained until the fade condition abates. This dynamic link maintenance capability affords the satellite system various performance advantages such as increased throughput and supported users and potentially reduced terminal/payload power requirements. Given a DCM system that controls coding, modulation and channel rate selection, these gains can be measured as increased spectral efficiency and increased burst rate capability.

While it is straightforward to quantify these gains on an individual link basis, the greater challenge is to understand the magnitude of these gains at a theater level. These gains will be dependent on the number, type and location of terminals that might be operating in theater, and the set of

DCM modes used. Link performance and DCM gains are also dependent upon the satellite architecture. This paper focuses on a regenerative satellite payload architecture where demodulation, decoding and forward error correction are performed by the payload. This architecture will be employed for TSAT. In a non-regenerative satellite system it would be necessary to know the quality of both uplink and downlink directions of the circuit since the aggregate performance of each half-connection would dictate link closure and DCM mode selection. Implicit in this architecture is that DCM gain is constrained by the weakest half-connection of the link. In contrast, a regenerative payload is simpler to operate and model because the link conditions for two nodes are decoupled. In terms of modeling link performance, the connections can be represented as terminal-payload and payload-terminal independent half-connections. This removes the need for a direction of traffic matrix to characterize end-to-end connections. Instead, it is sufficient to simply know where the terminals are relative to the satellite antenna gain contours. Randomly generated rain fades and mobility impairments can then be imposed to create a stochastic model of DCM behavior.

MODEL DEVELOPMENT

For this paper we chose a single AOR and scenario: major theater war, Korean peninsula, Army forces only. Terminal types modeled fell into three classes: COTM (Communication-on-the-move); COTH-Small (Communication-on-the-halt small); COTH-Large (Communication-on-the-halt large). There was a 6dB antenna gain difference between each class. The COTH-Small terminal had 7.5dB more EIRP than the COTM terminal. The COTH-Large terminal had 15dB more EIRP than the COTH-Small terminal.

A detailed view of the scenario is shown in Figure 1. The deployed echelons include 7 FCS and 6 SBCT brigade level units-of-action (UA), 6 division level units-of-engagement (UEx), two Corps level units (UExi) and one theater level echelon (UEy). Each of the units is equipped with varying types and quantities of SATCOM terminals deployed over the operational areas shown. For this analysis, all SATCOM terminals geographically located on the Korean peninsula. A total of 1,582 terminals were modeled, of which 59% were COTM, 36% were COTH-Small and 5% were COTH-Large.

The satellite, which was located at 155° East longitude, used a multi-beam antenna pattern containing 0.5° spot beams on a uniform grid. Figure 1 also includes a grid overlay that was used to randomly assign rain fade depth. Each grid is 25km square. All terminals within the same grid square were assigned the same rain fade to account for spatial correlation of rain fade events. This iso-loss grid method is considered a worst case approximation of spatial correlation. More accurate rain field modeling would be expected to improve the overall DCM gain results.

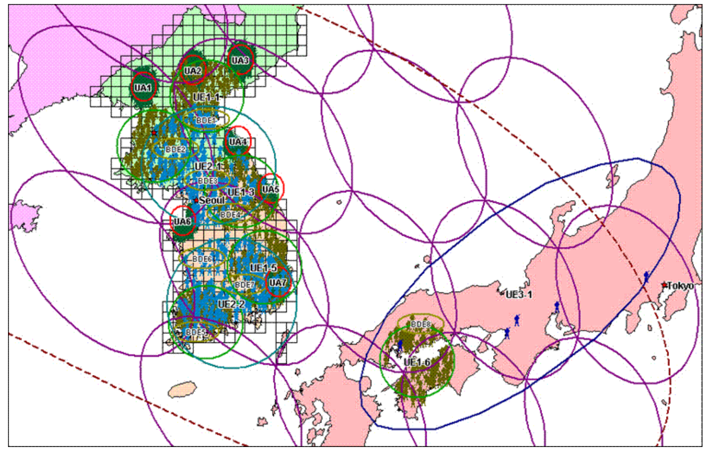

Figure 1. Scenario Overview

LINK BUDGET ELEMENTS

In the model, each terminal is assigned a latitude and longitude based on its unit location and unit operating area. Terminals are mapped to the satellite antenna beams with the highest satellite EIRP and G/T at the terminal location. Grids squares are assigned a randomly generated number between 0 and 1. This value is mapped to an availability which coupled with elevation angle, terminal location, and operating frequency are used to generate a grid square atmospheric attenuation using ITU models for atmospheric propagation. Figure 2 shows the EHF attenuation from 155° East into the Korean peninsula as a function of availability.

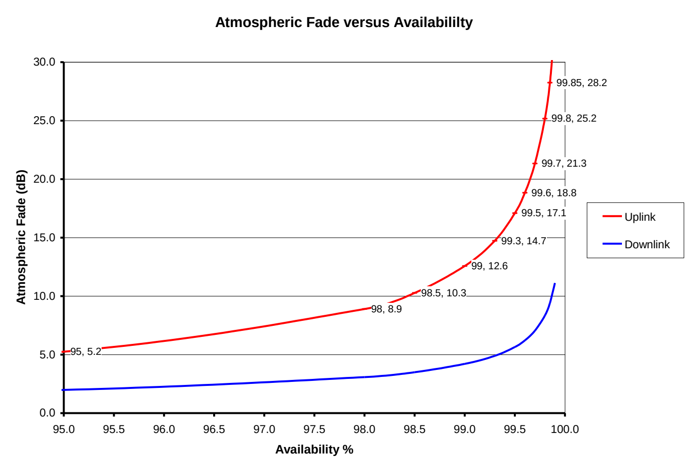

Figure 2. Atmospheric Fade Model

In addition to stochastic rain fade modeling as discussed above, a 3dB impairment for communicating while on the move (scintillation, partial blockage) was also included. This impairment was randomly assigned, affecting 50% of the COTM class terminals (not applicable to the COTH terminals).

DCM MODES

The DCM mode structure used in the model is summarized in Figures 3 through 5 for the uplink. Figure 3 describes the relative received power versus noise power spectral density (Pr/No) of each mode (relative to an arbitrary reference mode). Differences between modes reflect the combined influences of modulation, coding gain and channel rate. A similar data set exists for the downlink. The model creates a mode transition pattern versus fade depth based on these attributes and a "transition strategy". That strategy could be either: transition to maximize/maintain highest spectral efficiency; or transition to maximize achievable burst rate. For this study, the transition strategy was efficiency biased for uplink and burst rate biased for downlink. An example of this transition behavior is shown in Table 1 for the uplink, where the numbers in the matrix show the progression of modes (1st to last) as fade depth increases.

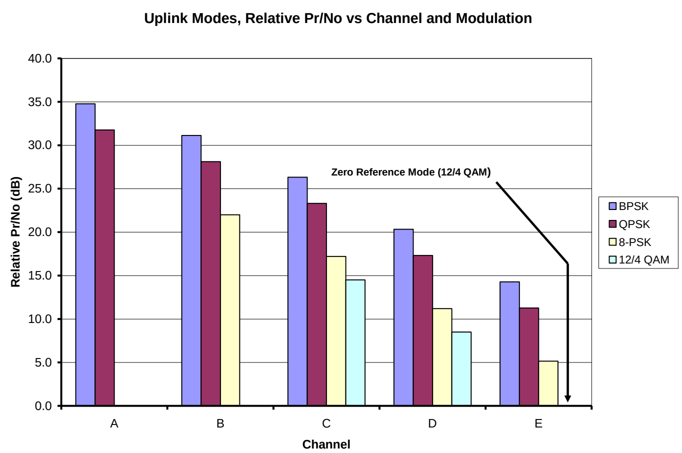

Figure 3. DCM Uplink Modes, Relative Pr/No

To define gain attributable to DCM, it is necessary to establish a reference point (mode) from which change can be measured. The reference would typically represent a mode that traditional static link provisioning strategy might employ to achieve a compromise between reasonable data rates and availability. Spectral efficiency gain would therefore be a ratio of the spectral efficiency of a mode to that of this reference. Achievable burst rate can also be viewed as a measure of DCM gain. DCM allows link operations at higher burst rates which translates for faster message transfer times and may allow higher packing efficiency in architectures employing resource sharing protocols such as DAMA (demand assigned multiple access). For this paper, the key data for the selected reference modes for uplink and downlink are shown in Table 2.

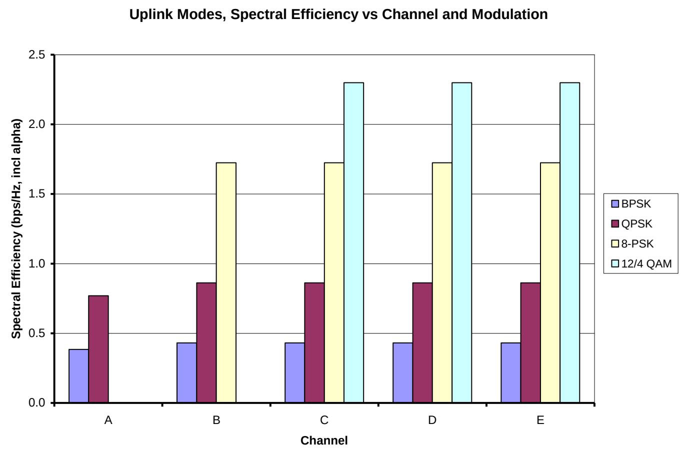

Figure 4. DCM Uplink Modes, Spectral Efficiency

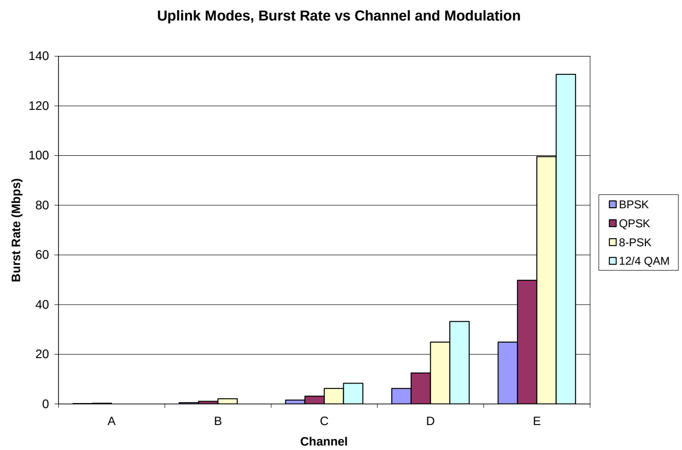

Figure 5. DCM Uplink Modes, Burst Rate

Table 1. DCM Uplink Mode Transition Example

COTM Uplink Mode Sequence; Criteria = Efficiency					
		Modulation Type			
		BPSK	QPSK	8-PSK	12/4 QAM
Channel	A	6	5		
	B		4	2	
	C		3	1	
	D				
	E				

Table 2. Reference Mode Data

	Reference Mode Data					
	Uplink			Downlink		
Terminal Class	Spectral Effncy	Relative Pr/No (dB-Hz)	Burst Rate (Mbps)	Spectral Effncy	Relative Pr/No (dB-Hz)	Burst Rate (Mbps)
COTM	0.86	28.1	1.04	0.86	18.0	18.66
COTH - Small	1.72	22.0	2.07	0.86	11.4	74.65
COTH - Large	1.72	17.2	6.22	0.86	8.4	149.3

RESULTS

The model generates various forms of output that describe the behavior of each terminal class, the probabilistic nature of the total fade represented in the scenario (total fade being a combination of off-boresite gain loss, rain fade and on-the-move degradation), and the theater overall DCM gain achieved. At the theater level, gain in spectral efficiency is weighted by burst rate to yield a bandwidth weighted average gain.

It was expected that the benefits of DCM would be sensitive to the robustness of the link design. Specifically, if the link design includes additional margin to increase robustness, then this should improve DCM gain (presuming the same reference mode). On the other hand, the more the links are starved of margin, the lesser will be the DCM gain. To quantify this, the results to be presented include a sensitivity study of DCM gain relative to link robustness.

Figure 6 shows a theater wide CDF of total fade experienced by the terminals. As an example from the graph, 98.4% of the terminals experienced a total fade of 12dB or less. Also reported on the graph is the peak fade experienced by a terminal(s) in the scenario, of 38dB (uplink). COTM fades of this magnitude will result in link failure.

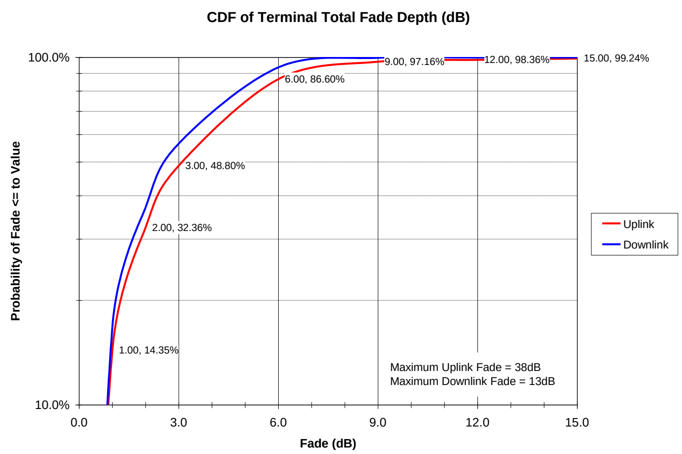

Figure 6. CDF of Terminal Total Fade

For each terminal class, the model generates a histogram of Delta Pr/No (difference relative to the reference), spectral efficiency gain and burst rate. Figures 7 through 9 provide results for the 932 COTM terminals in the scenario for the case where no bias has been applied to the link budgets. For the COTM class terminal class, nearly 80% of the terminals operated with an uplink spectral efficiency gain of 2.0. Figure 8 shows that only 2% of the terminals are operating using the reference mode (Delta Pr/No=0 dB-Hz), while 1% require an even lower order mode (Delta Pr/No > 0) for link closure. The average achievable burst rate across the theater for this class is 3.3Mbps on uplink and 29.1 Mbps on downlink. Figure 9 shows that 25% of the uplinks can sustain burst rates of 6.2Mbps which is six times the reference mode burst rate.

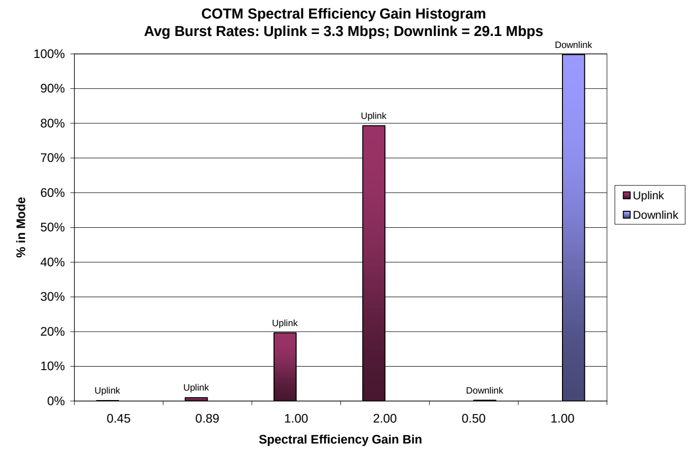

Figure 7. Spectral Efficiency Gain Histogram, COTM

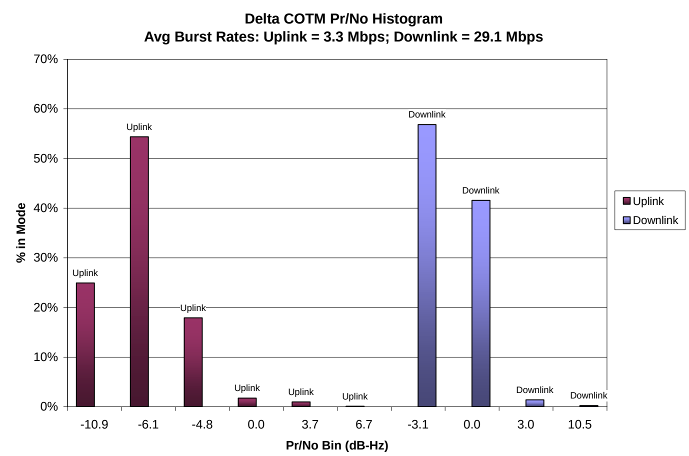

Figure 8. Delta Pr/No Histogram, COTM

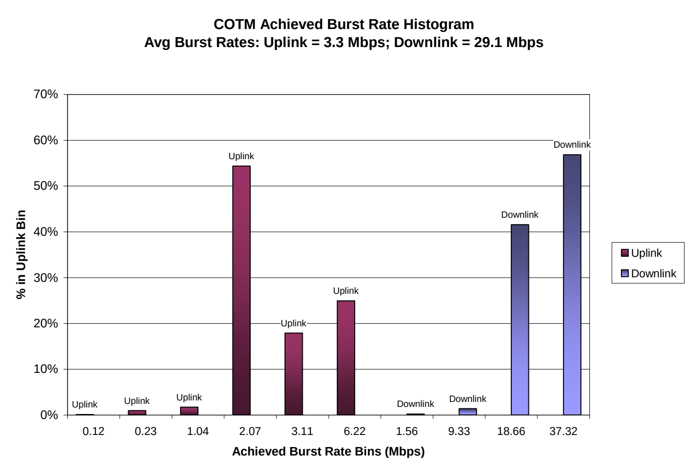

Figure 9. Burst Rate Histogram, COTM

Satellite links are typically designed with hidden margin for a number of link budget components. Hidden margin results from conservative design assumptions based on assumption that components are only meeting minimum performance requirements. It is not unusual for terminals and satellite payloads outperform minimum requirements by up to 1 dB or more. Multi-beam antenna systems, in particular, have been shown to have significantly better C/I performance than specified over most of their coverage area. Unfortunately, static link designs can not take advantage of this hidden additional margin and in some cases operate with 3 dB, or more, of additional link margin at Ka and EHF frequencies. Architectures employing DCM are continuously monitoring link conditions and therefore can take advantage of this hidden margin to operate in more spectrally efficient modes or with higher burst data rate. To quantify the additional gain associated with this effect, a series of runs were made using an identical set of fade conditions, but with a bias, hidden, margin added to the links. Bias margins as large as 6 dB were evaluated. For completeness we also evaluated cases with negative margins which would be representative of terminals or payloads under performing specification requirements. The mode transition behavior was revised for each bias case and then the scenario results were recomputed. DCM gains were computed relative to static operation at the 0 dB bias point. As expected, a more robust link allows more terminals to operate in higher order modes, increasing gain opportunity.

The results for this sensitivity study are summarized in tables 3, 4 and 5 for each terminal class.

Table 3. Link Robustness Results, COTM

	COTM Class						
	Uplink			Downlink			
	Metric			Metric			
Link Budget Bias (dB)	Spectral Effncy Gain	Average Burst Rate (Mbps)	% Link Failures	Spectral Effncy Gain	Average Burst Rate (Mbps)	% Link Failures
6	2.5	7.7	0.3%	1.2	106.9	0.1%
4	2.3	6.2	0.3%	1.0	73.4	0.1%
2	2.0	4.3	0.3%	1.0	47.3	0.1%
0	**1.8**	**3.3**	**0.5%**	**1.0**	**29.1**	**0.1%**
-2	1.5	2.1	0.5%	1.0	19.8	0.1%
-4	1.0	2.3	0.6%	0.9	11.8	0.3%
-6	1.0	1.4	1.6%	0.8	7.1	0.3%

Both uplinks and downlinks of the COTM and COTH-Small class terminals are sensitive to link robustness over the full +/-6dB range evaluated (recall that a positive bias represents a more robust link). These terminal types achieved theater average burst rates significantly greater then the reference mode for link robustness biases of -2dB and above. COTM uplink performance showed a spectral efficiency gain increase from 1.8 to 2.5 assuming 6dB of additional margin. Note that even at this level there is a non-zero link failure rate owing to the potentially high fade depths that can occur with EHF frequencies in this rain region. The uplink of the COTH-Large class terminal is relatively insensitive to these perturbations in link margin, which is not surprising given that these very large terminals are able to meet availability goals operating statically in very efficient 8PSK and QAM modulcations. The downlink spectral efficiency gains are more impressive for this class terminal.

Table 4. Link Robustness Results, COTH-Small

	COTH (Small) Class					
	Uplink			Downlink		
	Metric			Metric		
Link Budget Bias (dB)	Spectral Effncy Gain	Average Burst Rate (Mbps)	% Link Failures	Spectral Effncy Gain	Average Burst Rate (Mbps)	% Link Failures
6	1.3	31.7	0.0%	2.0	149.3	0.0%
4	1.3	31.4	0.0%	2.0	149.0	0.0%
2	1.3	24.4	0.0%	1.5	148.7	0.0%
0	**1.3**	**8.1**	**0.0%**	**1.0**	**141.2**	**0.0%**
-2	1.2	7.4	0.0%	1.0	96.3	0.0%
-4	1.0	5.7	0.0%	1.0	55.0	0.0%
-6	1.0	2.1	0.2%	1.0	35.3	0.0%

Table 5. Link Robustness Results, COTH-Large

	COTH (Large) Class					
	Uplink			Downlink		
	Metric			Metric		
Link Budget Bias (dB)	Spectral Effncy Gain	Average Burst Rate (Mbps)	% Link Failures	Spectral Effncy Gain	Average Burst Rate (Mbps)	% Link Failures
6	1.3	33.2	0.0%	2.7	199.1	0.0%
4	1.3	33.2	0.0%	2.7	197.7	0.0%
2	1.3	33.2	0.0%	2.2	166.6	0.0%
0	**1.3**	**33.2**	**0.0%**	**2.0**	**149.3**	**0.0%**
-2	1.3	32.5	0.0%	1.9	149.3	0.0%
-4	1.3	31.8	0.0%	1.0	147.3	0.0%
-6	1.0	24.4	0.0%	1.0	136.4	0.0%

To determine the statistical variance in these results, a 500 run Monte Carlo analysis was performed where the rain fade by grid square and the mobility impairment were a randomly re-assigned for each run. The results showed that these gains were reasonably invariant for large scale force deployments, with standard deviations of 2% of less.

The previous results showed the spectral efficiency and burst rate gains realized employing DCM for three different terminal types. To determine theater gain for an architecture employing dynamic resource allocation, such as TSAT, one must weight individual terminal gains by the busy hour bandwidth required by each terminal. This results in a bandwidth, or resource utilization, weighted estimate of gain. Such an approach has been implemented by the authors for the TSAT and WIN-T programs using the WIN-T Information Exchange Request database traffic model. For this analysis, we have approximated that traffic model by weighting each terminal gain based on clear sky burst rate. The final gain results for the Korean Theater are compiled in Table 6 as a function of the link robustness variable that was described previously.

Table 6. Theater Level DCM Gain vs Link Robustness

Burst Rate Weighted Theater Level Spectral Efficiency Gain		
Link Robustness (dB)	Uplink	Downlink
6	1.6	1.6
4	1.5	1.6
2	1.5	1.4
0	**1.5**	**1.1**
-2	1.3	1.1
-4	1.1	1.0
-6	1.0	1.0

Presuming that link implementation would most likely fall in the +3 dB to 0 dB robustness range, DCM offers bandwidth weighted spectral efficiency uplink gains of 50%; and downlink gains of 10% to 50%. For scenarios that are more bandwidth dominated by COTM class terminals, for example small operations, these uplink gains can approach 100%. For spectrum limited theaters, this represents a significant potential increase in supported users.

CONCLUSION

Given a major theater of war force deployment scenario, and a high rain rate region like the Korean peninsula, DCM enabled coding, modulation and channel assignment offers bandwidth weighted spectral efficiency uplink gains of 50% as a theater aggregate; downlink gains of 10% to 50%. For the COTM class terminal, the uplink gain is 80% to 100%, which is significant given the large number of COTM terminals that FCS would deploy in the transformed Unit of Action. In fact, DCM, along with dynamic resource allocation, are critical component to deploying large numbers of terminals Also significant to operational efficiency and end-user experience might be the dramatic increase in uplink burst rates achievable through the DCM enable use of higher order modes during low fade conditions.