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Future Digital Flexible and Software Defined Payload Systems

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Commercial digital payloads of the past were mostly limited to Mobile Satellite Services (MSS) applications due to the smaller service link bandwidth and reduced processing needs. These programs required beamforming and channelization either through on-board processors or ground based beamforming (GBBF) to provide flexible beam plans with significant frequency reuse over the coverage area. However in mid- 2012 Intelsat announced the EPIC platform and has since ordered multiple satellites with digital channelizers for FSS/HTS applications. SES has also recently ordered multiple satellites with digital transparent processing. These digital payloads increase the cost-effectiveness of the bandwidth for the operators by delivering more capacity to their customers. In addition, these systems are backward compatible and provide Single-Hop point-to-point options to support STAR and MESH network architectures. The flexibility of these payloads allow the operators to move what would otherwise be unusable or stranded capacity to coverage areas where it is needed.

The future vision of the Lockheed Martin RF Payload Center of Excellence* in Denver, Colorado, adds digital beamforming to the flexible channelization and routing to provide even more flexibility for the FSS and HTS operator to meet their capacity needs. These fully reconfigurable payloads also benefit the satellite manufacturer by allowing common product solutions to be built reducing the time from satellite order to launch.

The flexible digital and software defined payload satellite will allow the operators to shape and move beam coverage with digital beamforming as well as move bandwidth between the beams through subchannelization and switched routing. EIRP flexibility is achieved by maximizing beam directivities where the user traffic is located and using a combination of Multi-Port Amplifier (MPA) and hybrid matrices as well as antenna optics which allow more RF power to be delivered to the feed elements needed to form the desired beams.

This combination of features allows the payload to be reconfigured for different orbital slots; the ability to serve different combinations of missions and services simultaneously; and provides increased usable capacity, spectral efficiency, and interference suppression

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which results in more cost effective use of the limited, with respect to fiber optic networks, satellite bandwidth.

The industry is taking steps towards this goal by providing digital channelizers and transparent processors for the FSS market and digital beamforming with channelization for the MSS market.

To reach the future vision development advances are required: reconfigurable digital processors with more bandwidth per port and larger number of ports to support digital beamforming, Multi-feed array antenna optics with high efficiency HPA's and small Size Weight and Power (SWaP) tunable frequency conversions and filtering. This paper discusses these topics and provides an update on the trades and technologies.

Nomenclature

AFR = *Array Fed Reflector*
BSS = *Broadcast Satellite Services*
ADC = *Analog to Digital Converter*
DAC = *Digital to Analog Converter*
DC = *Digital Channelizer*
DCB = *Digital Channelizer Beamformer*
DRA = *Direct Radiating Array*
GaN = *Gallium Nitride*
HTS = *High Throughput Satellite*
MPA = *Multi-Port Amplifier*
MSS = *Mobile Satellite Services*

I. Introduction

Commercial communication satellite systems have been categorized as MSS (Mobile Satellite Services), FSS (Fixed Satellite Services), BSS (Broadcast Satellite Services and HTS (High Throughput Satellite Services) based on their frequency of operation and communication service provided. The satellite payload architecture for these satellites have generally been different to meet the specified mission. In recent years, the industry has been asking the satellite manufactures for expanded coverages, hybrid payloads with multi-bands, and increased flexibility to serve changing market demands. There has also been a blurring of the distinct line between the services provided with MSS operators needing to offer 4G or higher services, and FSS operators providing HTS services. The BSS satellites remain the most unique today, but with the provided digital services of FSS and HTS combined with multi-cast and regional beams some broadcast capability is also needed. Satellite operators and service providers continue to require increased capacity to remain competitive with terrestrial fiber, along with lower cost per bit and more flexibility.

The industry has recognized that digital channelization and beamforming which is changeable on orbit will provide the flexibility required to increase the effective utilization of the Satellite resources. Phrases such as software defined payload and digitally beamformed flexible payloads are being commonly used in conferences and business discussions as a goal towards meeting these increasing demands on the satellite design.

Commercial digital payloads of the past were mostly limited to Mobile Satellite Services (MSS) applications due to the smaller service link bandwidth and reduced processing needs. These programs required beamforming and channelization either through on-board processors or ground based beamforming (GBBF) to provide flexible beam plans with significant frequency reuse over the coverage area[2]. In this way these systems are able to provide enough capacity given the limited service link bandwidth. However in mid- 2012 Intelsat announced the EPIC platform and has since ordered multiple satellites with digital channelizers for FSS/HTS applications. Shortly thereafter SES placed orders for satellites with digital transparent processing and currently has several satellites with these digital payloads being built. These digital payloads increase the cost-effectiveness of the bandwidth for the operators by delivering more usable capacity to their customers. This allows the operator to increase the total bandwidth sold, and correspondingly their return on investment. In addition, these systems are backward compatible, and also provide Single-Hop point-to-point options to support STAR and MESH network architectures. The flexibility of these payloads allow the operators to move what would otherwise be unusable or stranded capacity to coverage areas where it is needed.

Our future vision for flexible satellites adds digital beamforming to the channelization and routing to provide even more flexibility for the FSS and HTS operator to provide useful capacity to the service providers and users of the satellite communication system. This fully reconfigurable goal also benefits to the satellite manufacturer by allowing common product solutions to be built with the potential for reducing the time from satellite order to launch.

Figure 1. Services Merging

The flexible digital and software defined payload satellite will allow the operators to shape and move beam coverage with digital beamforming as well as move bandwidth between the beams through subchannelization and switched routing. EIRP flexibility is achieved by maximizing beam directivities where the user traffic is located and using a combination of Multi-Port Amplifier (MPA) hybrid matrices as well as antenna optics which allow more RF power to be delivered to the feed elements needed to form the desired beams. This combination of features allows the payload to be reconfigured for different orbital slots; the ability to serve different combinations of missions and services simultaneously; and provides increased usable capacity, spectral efficiency, and interference suppression which results in more cost effective use of the limited, with respect to fiber optic networks, satellite bandwidth.

The industry is taking steps towards this goal by providing digital channelizers and transparent processors for the FSS market and digital beamforming with channelization for the MSS market. To reach the future vision development advances are required: reconfigurable digital processors with more bandwidth per port and larger number of ports to support digital beamforming, Multi-feed array antenna optics with high efficiency HPA's and small Size Weight and Power (SWaP) tunable frequency conversions and filtering. This paper discusses these topics and provides an update on the trades and technologies.

II. Future Flexible Payload Goal

The pinnacle of success for the software defined payload is to provide full flexibility of beams, coverages and frequency bands with a Terabit-per-second or more of deliverable capacity from any orbital slot and supporting any mission services which may be imagined. In addition to the robustness, flexibility and increased capacity, it also includes short cycle time between the ordering of the satellite and the commencement of the communications service. While this goal may never be fully achievable, it is useful to set a direction for development and to stimulate the creativite engineering in the satellite industry.

The future goal may be categorized in two areas:

1. Mission Performance, Increased Capacity, Flexibility and Robustness
2. Reduced satellite Order to On-orbit Service Operations Schedule Time.

The satellite payload is reconfigurable to adjust beam plans, beam shape, number and size, with the ability to move capacity (power and bandwidth) to match traffic demands for current and new services. This will allow a satellite to provide multiple mission services and be reconfigurable to support moving to new orbital slots for fleet management in case of failures, and also to develop new service offerings.

An example payload block diagram is shown in Figure 2. This payload example has a combination of fixed beam antennas and on-board flexible beamforming. The Digital Channelizer Beamformer (DCB) would provide the functions of channelizing the spectrum and routing the selected bandwidth between beams to match the traffic demands and increase the fill percentage of the payload resources. The DCB would also include the beamforming and calibration functions which work in conjunction with the Antenna Optics and MPA to provide the beam and power flexibility to match the EIRP with the traffic demands. Beam plans can easily be changed through changes in the channelizer routing, beam weight coefficients and gain control settings.

An example Array Fed Reflector (AFR) is shown on the diagram which provides the multiple feed elements needed for the beamforming. An eight-by-eight MPA is also shown which provides the power flexibility. The DCB also includes linearization algorithms and Virtual Input Hybrid Matrices to work with the MPA configurations.

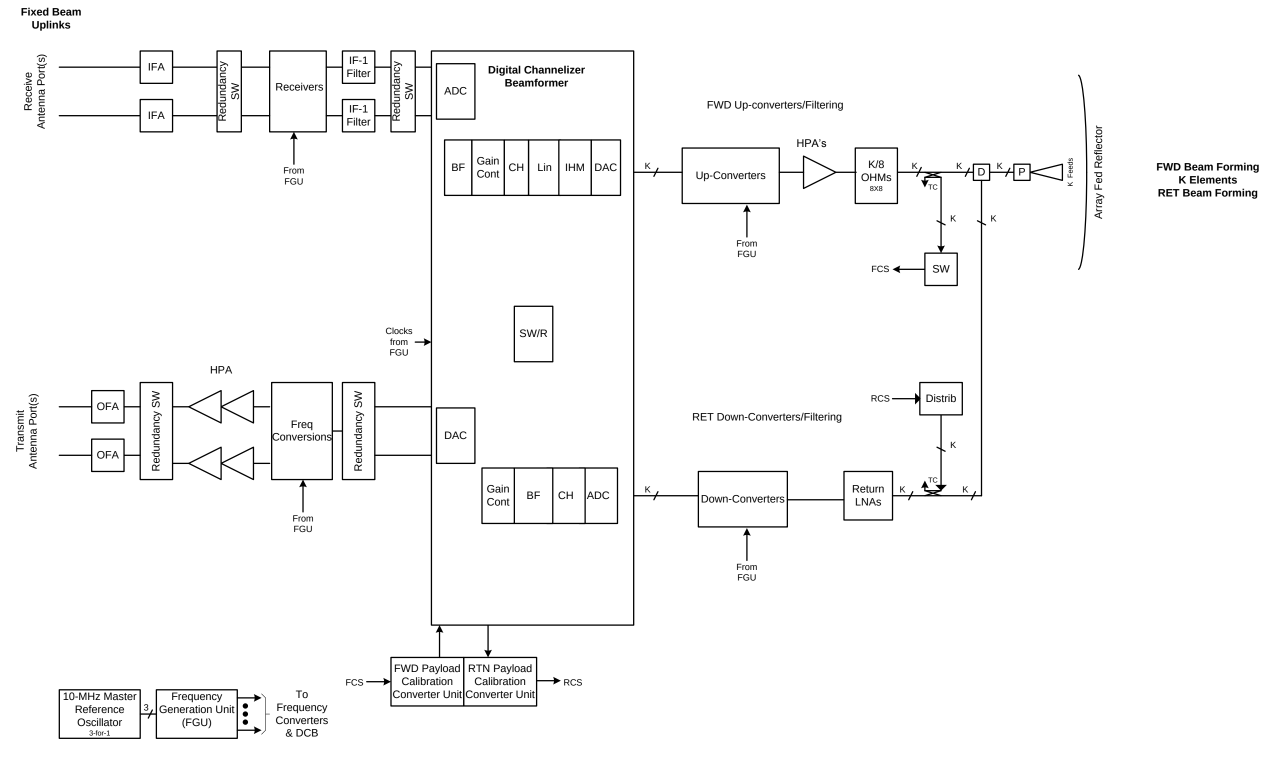

Figure 2. Example Flexible Payload block diagram

These future payloads provide the potential for a significant reduction in the Satellite schedule time from order to delivery. In the past the payloads were highly customized to provide the beam plan and switching needs for specific missions. The new flexible payload makes use of the same building block elements to satisy multiple missions and multiple orbital slots. In addition the DCB calibration functions may be used to reduce the integration and test time of the satellite through integrated built in self test at the chip, module, unit, subsystem and system level.

III. Technologies Needed

The following systems engineering methodologies, tools and expertise along with hardware technologies are required to implement this vision.

1. End-to-end Communication Mission Systems Engineering Tools and Methodologies
2. Digital Payload Systems Engineering Tools and Methodologies
3. Scalable and Reconfigurable Digital Channelizer Beamformer Products
   -Reduced SWaP with increased functionality, port number and bandwidth over current products
4. Flexible frequency conversions and filtering products

-Small SWaP integrated common tunable converters and filters

5. Antenna Optics and HPA products to support flexible beamforming over global and defined coverage areas
   -Flexible Antenna design and optimization tools and methodologies
   -Full Coverage, Regional, Wide and Narrow Spot Beams
   -High efficiency and high linearity GaN SSPA's
6. Integrated I&T process with Built in Self-Test at device, module/board, unit, subsystem, system level
7. Global Resource Management Systems
   -Allows operator to model, measure and reconfigure the flexibility

A. Flexible Antennas

The flexibility of the beam forming is accomplished through a combination of the antenna optics and the beamforming network. Multiple feed elements beamlets are combined in amplitude and phase to create the desired formed beam. Flexibility to provide narrow spot beams, larger spot beams, regional beams and full coverage beams is provided. Two antenna classes are suited to provide multiple beams with flexible shapes for flexible payloads: Array Fed Reflectors (AFR); and Direct Radiating Arrays (DRA).

Array Fed Reflectors are one class of antenna optics to be used in the flexbile payload architectures. The narrowest spot beam and the full coverage beam set the limits for the antenna subsystem. The narrowest spot beam needed defines the aperture size for the antenna and the desired coverage area defines the number of feed element beamlets. Antenna engineering tools are used to optimize the reflector size and shape, the feed element size and spacing, the F/D and amount of defocusing. Trade-offs between the number of feed element beamlets and the formed beam directivities, sidelobe control and edge of coverage performance are critical. Reducing the number of feed elements saves digital processing power in digital beamforming as well as the payload frequency conversions and amplification equipment.

In typical applications many dozen to several hundred feed elements are required. Applications requiring high composite EIRP and small spot sizes tend to require larger numbers of feed elements. For a fixed number of feed elements there is a trade between coverage area and spot size.

In many AFR applications it is desireable to use defocused antenna optics. This increases the quantity of feed elements associated with each beam and reduces the dynamic range associated with each feed element. The dynamic range required by each power amplifier in a transmit DRA may be further reduced by implementing the power amplifiers as MPAs. Even so the dynamic range and linearity required of each power amplifier drives amplifier efficiency and the power consumption of transmit AFRs. Applications requiring a high portion of the traffic capacity to be focused into a small portion of the coverage area will require higher output power from each amplifier and larger power amplifier dynamic range than applications where the traffic distribution is more uniform.

Another antenna class which provides high flexibility is the Direct Radiating Phased Array Antenna (DRA). This antenna class can form spot beams and shaped beams. Coverage areas may be contiguous or non-contiguous. Both the intended coverage area and regions requiring low sidelobe levels may be shaped. The minimum feature size for beam shaping is of the order of the 3 dB beamwidth of the narrowest spot which may be formed by the DRA.
A major benefit associated with DRAs is that all elements within the array contribute to all beams. This makes the DRAs relatively insensitive to RMS errors and failed elements. In many cases it is possible to operate a transmit phased array with the same RF power level in every output amplifier. This power level is substantially independent of the beam locations. This feature makes it possible to achieve higher amplifier efficiency than is possible for amplifiers which have to operate over a wide range of output powers.

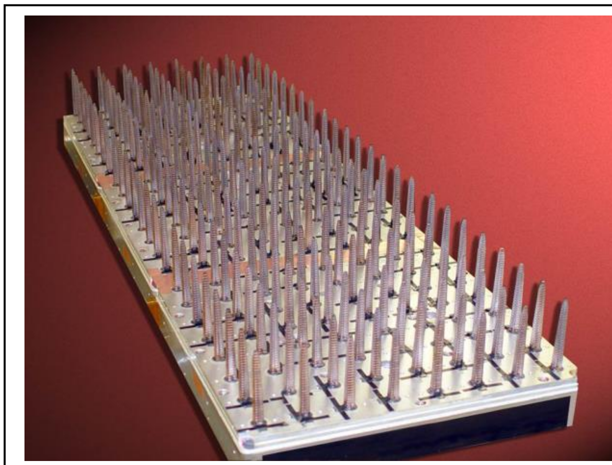

Figure 3. 17.3-17.8 GHz 2 beam receive DRA

Another feature which helps minimize transmit array power consumption, when operating with multiple signals being broadcast to different locations, is the ability to manage the traffic in a manner which spreads the intermodulation products in the far field of the antenna. This permits the amplifiers to operate at a more non-linear operating point whilst maintaining a desired signal to interference level at the receive stations.

For transmit DRAs the composite spot beam EIRP increases with the square of the number of elements in the phased array, because increasing the number of elements increases both the antenna gain and the total RF power in free space. The cost, mass and power consumption of transmit DRAs scale linearly with the number of elements. This makes transmit DRAs particularly attractive for point-to-point communications systems requiring high composite EIRP.

Figure 3 shows a 17.3 – 17.8 GHz two beam receive DRA which was launched on AMC14 in March 2008 [1]. This 8” x 24” antenna demonstrated a G/T of ~ 6 dB. It is comprised of 3 modular subarrays called Supertiles. Each Supertile contains 16 LNAs, a four beam beamformer, control interface and power supply.

The major negative with DRAs is their cost. Advances in semi-conductor technology, packaging technology and automated assembly of sub-arrays are all contributing to substantial reductions in the cost of DRAs. Another consideration for the DRA is the number of elements and the number of beams. With the beamforming performed in the DRA, the number of beams drives the complexity and cost. If the DRA is combined with the digital channelizer beamformer the number of elements drives the processor complexity and cost. The AFR has the advantage of reducing the feed element count for the DCB when the number of beams needed is very large.

B. Flexible Frequency Conversion and Filtering

The block diagram in Figure 2 illustrates that many upconverters and downconverters are required to connect the DCB to the multitude of antenna feed elements at the service link frequency. In order to realize the satellite schedule savings an approach to commonality is needed which covers the different frequency ranges and bands that any specific satellite build will need to cover. The DCB provides the channelization, so the conversion filtering only needs to provide the selection of the service link bandwidth into the ADC and out of the DAC that will be beamformed and channelized. For example, 500 MHz Ku assigned band would require a 500 MHz tunable filter converter unit.

A highly integrated multi-pack RF approach with synthesized LO’s and wideband RF components can provide a common building block. This approach might use a fixed filter that is selected and installed into the unit after satellite order and before the test campaign. Several bandwidth selections could be made available for rapid product final assembly. The choices of filter selection is driven by the total service link bandwidth range, the amount of bw to be channelized and beamformed within the DCB, and the amount of BW that would be fixed switched outside of the DCB unit. This could limit the number of filter selections to the order of 4 or 5 for the majority of satellite offerings.

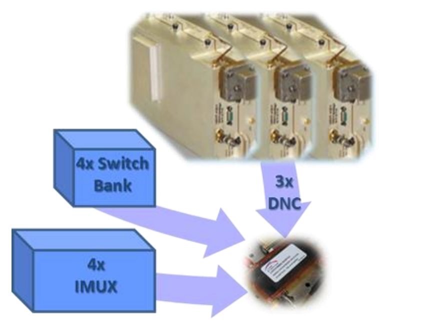

Figure 4. Photonics reduces SWaP

A photonic approach to frequency conversion and filtering offers the most flexible and lowest cost approach to the complex analog signal processing needs of a future software defined payload. The SWaP savings are significant as shown in Figure 4. This is a result of two intrinsic characteristics of photonics that cannot be imitated with traditional RF approaches, both of which result from the 10,000x reduction in wavelength of an optical vs. RF signal. First, the much shorter wavelength enables drastic reductions in the sizes of wavelength dependent components such as filters and waveguides, leading to 10x or more reductions in individual component sizes. Second, the translation in frequency space to a 10,000x higher carrier eliminates the fractional bandwidth limitations that typically constrain the operational bandwiths of traditional analog RF circuits and functions. This is easily observed in electrical-optical and optical-electrical conversion devices which are readily available with electrical bandwidths of multiple 10s of GHz. This bandwidth equivalence extends into solely photonic devices such as filters, switches, and transmission media as well, enabling a photonic processing approach to tune rapidly over

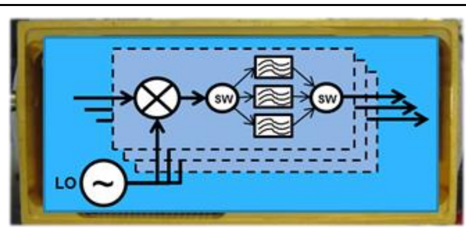

Figure 5. Photonics tunable converter filter

multiple 10s of GHz while maintaining low loss and flat frequency response.

For example, an RF photonic filter with a given optical frequency response such as shown in Figure 5 can be tuned through frequency conversion to operate with any RF frequency bounded by the E-O and O-E device frequency constraints. Lockheed Martin has demonstrated single step frequency conversion through a photonic filter that is tunable from 2x the IF frequency to as high as 65 GHz. Finally, the small size of photonic components affords a higher level of integration, giving the payload designer the ability to build and test the software defined payload functions at the component level, substantially reducing costs at satellite integration and test.

C. Digital Channelizer Beamformer

Digital channelizers and digital channelizer beamformers have been flown in space as discussed earlier. The future goal increases the total bandwidth and port counts which drive the processing requirements significantly higher. Therefore, a stepping stone approach to reduce the total processing requirement is envisioned with a hybrid payload solution which partitions the total beam bandwidth into three flexibile categories :

1. A subset of the beams and bandwidth to provide the full digital channelized beamforming functionality.
2. A second subset of beams and bandwidth with channelization and routing only.
3. A third subset of beams and bandwidth with selectable beam and bandwidth through RF switches and filters.

The satellite industry previously used the third method to provide flexibility and has recently extended this to the second category. The nearer-term future goal would increase the amount of beams and bandwidth that could be covered with the digital channelizer (Category 2) and add the first category (digital channelization, beamforming, and routing) to the satellite payload.

The Digital Channelizer alone provides important benefits to the satellite service provider, which are increased even further with the DCB. The channelizer routing function allows the service provider to increase the satellite fill percentage by providing the flexibility to move bandwidth and connections to match the user demand. In addition point-to-point capability is provided to support both MESH and STAR network services.

The DCB adds the flexibility to change the beam size, shape and pointing to provide capacity where you need it, when you need it. In addition to increasing the filled capacity, the total potential capacity is increased through increased beam directivity to the users served and higher frequency reuse with interference suppression techniques. The edge of beam rolloff can be reduced with smaller cell sizes as well as the flexibility to dynamically point and shape the beams to match the active user locations.

A measure of the DC and DCB processing size can be defined as the total signal bandwidth processed. For example, a symmetric channelizer which processes 250 MHz in 20 beams corresponds to a 5 GHz channelizer. If the same 250 MHz service bandwidth was used with the DCB, the multiplier becomes the number of feed elements rather than the number of beams. So 250 MHz per feed element times 100 feed elements becomes a 25 GHz digital channelizer beamformer.

The DCB processing size becomes large, quickly as the coverage area increases. For example a ½ earth Ku band system might need 120 elements and if dual pol 500 MHz bandwidth is allocated that corresponds to a DCB size of 120 GHz.

The example block diagram shown in Figure 2, also shows fixed beams which are required to be switched in with the DCB, so the processor size increases accordingly. In some cases, fixed GW beams will be the preferred architecture with the flexible beamforming left for the user traffic.

Understanding and quantifying the processing size needs in the future is extremely important as the DC and DCB products must be modular and scalable to meet the schedule and cost goals for the future flexible satellite. The currently flown commercial products have relied on ASIC's to do the heavy lifting of the DSP algorithms, along with FPGA and CPU functions for the control and lesser demanding functionality.

Technology	Company	Type	Node (nm)	Relative Power Consumption*
FPGA	Xilinx	V5-SIRF	65	1.00
FPGA	Alterra	A7	28	0.46
FPGA	Xilinx	V7-980T	28	0.43
ASIC	BAE	RH45	45	0.51
ASIC	IBM	Cu32	32	0.11

*Application = filter bank

Figure 6. Technology Node Comparison

Advances in FPGA technology have led to

some designs which do not require the ASIC(s). Since the ASIC design phase is costly in both dollars and schedule time, the FPGA solution provides lower cost, reduced schedule time for new developments. Further without the ASIC's, the FPGA solution is fully reconfigurable. Whereas, with the ASIC the system engineering must be done properly to ensure the needed flexibility is provided in the product design. Determining the timeline needs, the processing needs and the cost target needs will ultimately drive the decisions of which technology nodes to develop and how much of the future goal can be realized when.

Figure 6 shows a comparison of several FPGA and ASIC technology nodes. This table is only part of the story as the ADC and DAC, high speed interconnect and thermal design of the boards and chassis are also key factors in the total unit SWaP.

The larger processing requirements of the full earth coverage Ka Band HTS system will likely require ASIC's to be included in the digital processing unit for a reasonable size, weight and power product. However, the smaller processing requirements of the MSS satellite systems, or the FSS channelized system can be accomplished without the ASICs.

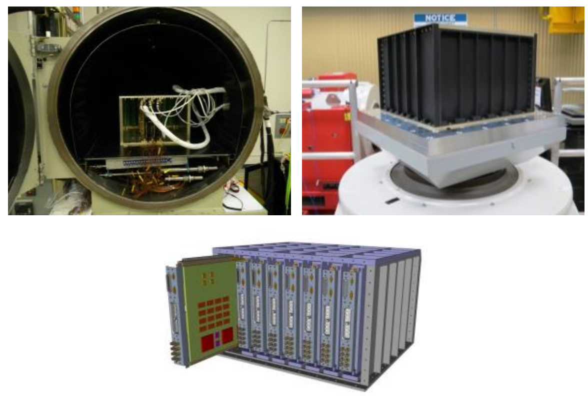

Figure 7. RAMP Unit in Environmental Test

Lockheed Martin initiated a fully reconfigurable FPGA product development in 2009 called the Reconfigurable Advanced Mission Processor (RAMP). This product uses radiation hardened FPGAs to provide a scalable DSP array, interconnected with a multi-terabit per second data transport. The RAMP concept and design is modular and scalable to meet a wide range of mission applications.

The DSP requirements of current and future missions can be met with relatively short development schedules, low engineering cost and the ability to evolve functionality on orbit throughout the system life. Figure 7 shows the RAMP unit modular product along with the unit in thermo-vacuum and vibration environmental testing.

The chassis and backplane slot quantity is scaled to meet the mission requirement needs for a particular range of service offerings. The reconfigurable processor module (RPM) contains the core signal processing FPGA's as well as daughter cards for the ADC and DAC I/O connections.

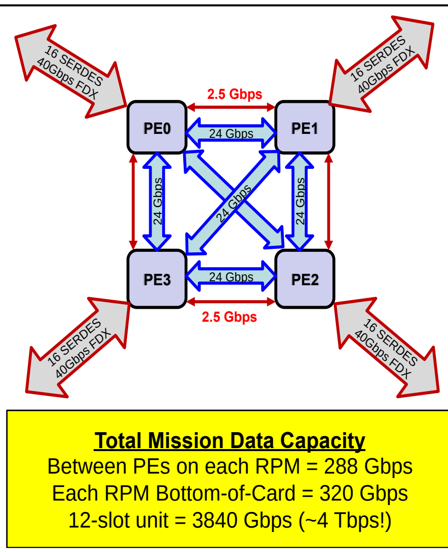

Figure 8. Processing Element Interconnect

Each RPM contains four FPGA's with associated high capacity and high bandwidth/low latency memory referred to as a processing element (PE). Each of the four PE's are interconnected with a full-mesh 24 Gbps full-duplex serial interface providing 288 Gbps of interconnection for the mission data processing as illustrated in Figure 8. Additional data interconnects are available when required. SERDES interfaces are used to interconnect between the RPM's. A 12-slot RAMP product can support approximately 4 Terabit per second of signal processing interconnections, with 48 FPGA's for the DSP functions.

D. HPA's

The block diagram in Figure 2 illustrates that K active HPA elements and K active LNA elements are needed for the digital beamforming payload where K is the number of feed elements. As discussed in the Antenna Optics section, K is a function of the antenna optics, the total coverage area, the smallest beamwidth desired, and the gain of the antenna. K can vary from 50 to several hundred for the AFR, and in the tens of thousands for DRA solutions. Thus, smaller packages, high efficient amplification is needed as a building block for the future flexibile payloads.

Gallium Nitride GaN solid state microve technology for SSPA's and show promise as the target technology for these products. One of the key aspects of GaN is the RF power output to size ratio is very high. GaN has five to ten times the RF power per device size compared to GaAs technology. GaN has the following advantages:

- High RF drain impedance, which results in lower-loss output matching networks
- High bandgap, high drain-to-gate breakdown = higher voltage/RF input power handling
- High operating temperatures using SiC host substrate, allowing higher power density
- Higher power/device in a single package; reduces RF combining losses
- Reduced DC current, improved DC/DC converter efficiency
- Improved linearity, efficiencies approaching TWT efficiencies (> 50%)
- Equal or higher reliability than GaAs ($>10^{10}$ hour lifetimes at Tch = 125 C)

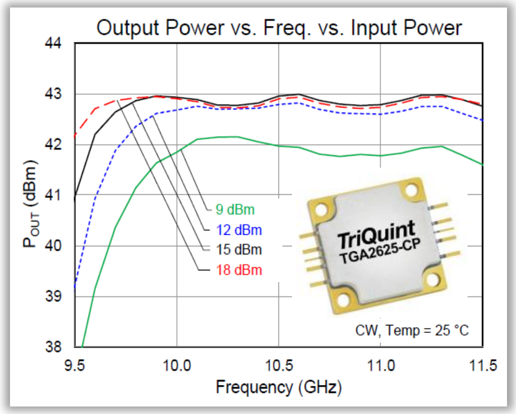

Figure 9. GaN SSPA MMIC Performance

In addition GaN supports the smaller modular HPA need with higher gain devices which reduce the part count, mass, and complexity of RF driver stages, and reduce the tune time needed due to more optimal device impedances than GaAs products.

Multiple suppliers have GaN HPA's that they are offering today or showing products on their roadmaps. These amplifiers cover the frequency ranges from L-band through V-band. Figure 9 shows an example of Triquint Ku-band SSPA MMIC which provides 20% bandwidth at 20W RF power.

E. Spacecraft Considerations

Depending on the unique payload technologies employed, and the overall size/capacity of the payload involved, flexible payloads can be accommodated using appropriate satellite design provisions and implementations.

As with most satellite communications payloads, flexible payload antenna accommodation is one of the most impactful and significant design drivers. Specifically, the antenna frequency bands of operation combined with required beamlet sizes dictate the required primary aperture physical sizes for both AFR and DRA type flexible payloads. Physics dictates that the lower the frequency band and the smaller the component beamlets required, the larger the physical antenna aperture is required. Since the area available for earth facing antenna apertures on the typical geostationary communications satellite is limited (Figure 10 depicts typical satellite level constraints for solid antenna reflector mounting), beamlet sizes and the number of independent antenna apertures may be constrained as a function of operational frequencies. Therefore the level of flexibility, meaning the range of frequencies and missions a given satellite will be able to cover, will be dependent on industries' ability to design wideband and multipolarization AFR and DRA antennas. It will also depend on satellite level designer's ability to accommodate the aperture sizes and corresponding multifeed arrays used to illuminate these apertures for AFR antennas.

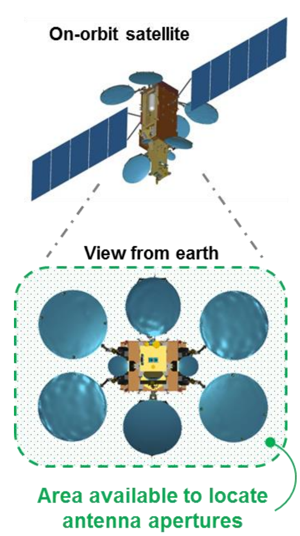

Figure 10. Apertures

Physical and thermal accommodation of payload processors also dictate key flexible payload spacecraft accommodation considerations. Depending on processor capacity, technology, and architecture, as well as specific thermal design, the spacecraft equipment mounting panels may need to include special features such as:

- Areas of localized mechanical reinforcements for especially dense and heavy DCBs
- Areas of increased thermal flux handling capability and heat spreading
- Satellite thermal radiators sized to support relatively low (versus typical payload communications equipment; e.g, high power amplifiers) DCB baseplate temperatures and/or lower temperature thermal zones that have been decoupled from those used for other spacecraft equipment.

Likewise, payload architectures that enable flexible beam forming often require large numbers of physical amplifiers/SSPAs. In the case of DRAs, these are often located on the antenna aperture and therefore free up space on spacecraft equipment mounting panels that may be used to mount other payload or bus equipment.

For AFR based payloads that employ MPA type amplifer configurations however, large amounts of equipment mounting area are required. As with most other payload types, spacecraft accommodation designs that minimize cable/waveguide run lengths between high power amplifiers and antenna feeds/elements are extremely valuable. The large numbers of amplifiers employed makes this design problem especially challenging, but also an especially big oportunity, in creating efficient flexible payloads spacecraft accommodations.

Lockheed Martin's latest A2100 bus provides features intended to help meet the unique flexible payload accommodation challenges. Specifically, the latest version of A2100 relies on a "Payload Centric" equipment mounting and thermal control system that allows for overall increases in satellite thermal capacity through the use of:

- Advanced ("self cleaning"), low end of life absorptivity, Optical Solar Reflectors (AOSRs)
- Improved East/West thermal energy transport enabled through the use of Lockheed Martin proprietary flexible heat pipe technology

As a result of these enhancements, A2100 is now able to mount larger amounts of payload equipment and reject greater amounts of thermal waste without the need for expensive and heavy deployed thermal radiators. Additionally, the latest A2100 equipment panel geometry provides the ability to minimize payload high power output losses by placing amplifiers closer to antenna radiating elements.

The use of Photonic payload elements can result in dramatic improvements in satellite level payload accommodation issues. As highlighted earlier in this paper, the photonic components typically are at least 10 times smaller than the corresponding RF devices they replace. For payloads that require significant amounts of low power input network filtering and switching, the use of photonics dramatically reduces the amount of spacecraft equipment panel mounting area required. This significantly reduces the portion of the satellite's mass dedicated to these low power input network functions. These mass and size reductions can be used toward many ends including increasing the total amount of payload equipment and therefore capacity launchable given a fixed launch vehicle/satellite capability and cost.

F. Global Resource Management Systems

The approach to integrating the flexible satellite payload as a node in the total communication network is especially important [3] and special software tools are required to take full advantage and provide the maximum capacity of these satellite systems. This suite of tools is called the Global Resource Management Systems with the integrated user interface referred to as the Global Resource Manager (GRM).

The GRM is used by the operator of the flexible and software defined payloads for the three purposes:

1. To **Model** scenarios
2. To **Measure** performance and use of the system
3. To **Configure** the System for particular scenarios

The model phase is also used before launch and operations begins. This is used by the system architect and the satellite communications system customer to determine the satellite and ground segment architecture and specific build configurations to meet the customer requirements. These requirements would typically consist of known scenarios and flexibility range. Even with the extreme flexibility provided, there will be limits such as frequency bands, coverage areas, and maximum throughput which will define the specific instantiations of equipment that are built up on the payload and launched.

The modeling capability considers the coverage area, frequency bands, smallest beam size, cell layout and frequency reuse plan, modulation and coding, terminal sizes, total throughput, traffic loading, capacity and availability. The Modeling functions have two categories of scenario development: Evaluation and Optimization.

Evaluation functions take the scenario parameter values and calculates the metrics used for the design trades and operational configuration trades. The evaluation functions operate on input data files and perform calcuations of system and subsystem performance which are useful for scenario planning and design configuration trades. For example, elementary secondary feed element pattern files for array fed reflector antenna architectures would be supplied as an input file to the GRM modeling tool. The evaluation function would use beamforming coefficient weight input files to create the formed beam pattern data. Other input files would define the frequency reuse plans, the cell polygons and beam assignments, traffic distribution within each beam and so on. The outputs of the evaluation functions would include beam gains and sidelobe performance, Transmit and receive C/I, total capacity of the system and capacity per beam, link margins and availability and any other result useful for making decisions on configurations.

The Optimization Functions within the GRM Modeling element would include routines to determine the beamforming coefficients including within the cost function criteria for system performance such as co-frequency reuse cell plan, Matrix Power Amplifier (MPA) loading and payload RF resources, multiple terminal types and modulation coding. These tools will also include the ability to optimize cell layout and frequency reuse plans to maximize capacity to serve a defined traffic requirement scenario. The cost functions would include regulatory constraints, suppression and interference requirements along with service quality and link margins.

Resource management will also be included considering the frequency spectrum available, the feeder link frequency to beam mapping, subchannels and sub-bands to beam mapping, power contraints, service quality, time of day and access control. Joint optimizations of beamforming beam plans and resource allocation will be possible.

The modeling phase evaluates plans through reported metrics such as capacity, link margins, payload power levels and loading, and delivered bits to users for various traffic scenarios. Scenario based evaluations results in configuration files that will be stored for configuring the Satellite and Gateway elements.

The measuring and configuring functions require the GRM to be integrated into the Satellite communication system network. Figure 11 depicts the GRM in the network. The lines indicate the interfaces between the GRM and the elements in the network. The GRM communicates to the satellite through the DCB Payload Management Link. This is an in-band signaling function with higher data rate that the Satellite T&C subsystem. The higher data rate is needed to provide the dynamic flexibility of these systems.

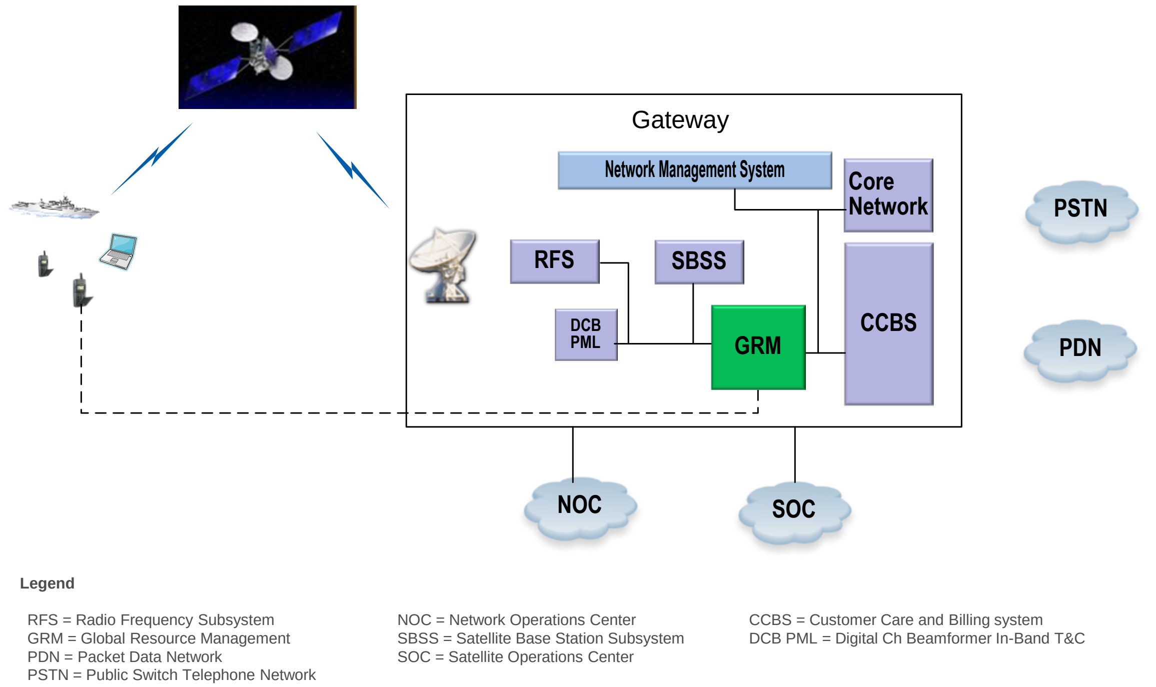

Figure 11. GRM interfaces within the Satellite Communications System

The Configuring functions take the stored configuration files from the Modeling phase and send commands to the network elements to execute the plan. The DCB must be commanded for the routing control and bandwidth selections for each beam. Likewise the Satellite Base Station Subsystem must be commanded to assign frequencies to the beamplan mappings and communicate with the terminals to provide those connections. The SBSS would configure the terminals as needed based on the information received from the GRM. The commands define the feeder link frequency to beams, sub-band to beam mapping, beamforming coefficients, etc.

The Configuring functions have security control and access management measures to prevent unauthorized configurations. Network plans developed through the modeling activities are loaded and executed. The DCB is commanded through the Payload Management Link (PML) to load beam coefficients, subchannel and subband gain and routing tables as well as feeder link to beam mapping. The SBSS is commanded through the Network Management System (NMS) to assign beam plans with frequency ranges per beam, feeder link to beam mapping and the modulation and coding allowed ranges. The terminals are configured through the SBSS control protocols. The Gateway Radio Frequency Subsystem RFS is also commanded through the NMS for items such as uplink power control and feeder link frequency plans.

The Measuring function collects information about the system and computes statistics for evaluation of network efficiency and to use in modeling scenarios for better utilization of the system capabilities to provide increased revenue for the system operator or operators. The GRM interfaces for commanding the configuration are also utilized to provide resource data as telemetry. Information on payload resources, network resources, SBSS resources and terminal resources can be obtained. In the future, this information could be fed into cognitive systems for enhanced operations through automatic reconfigurations. In the nearer term, it is expected the information will be used for modeling scenarios to improve capacity and services offered.

IV. Conclusion

Flexible payloads of the future will provide increased capacity, assignment of capacity where you need it, when you need it and the ability to reconfigure for different orbital slots and mission services. In addition, the reconfigurability and modular scalable hardware elements allow the satellite manufacturer to decrease the schedule time from satellite order to in-service operations. System techniques, tools and hardware technologies are advancing toward this goal. The first implementations are expected to be hybrid solutions which partition the total beam bandwidth into three flexible categories: A subset of the beams and bandwidth to provide the full digital channelized beamforming functionality; A second subset of beams and bandwidth with channelization and routing only; A third subset of beams and bandwidth with selectable beam and bandwidth through RF switches and filters.

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*The RF Payload Center of Excellence based in Denver, Colorado, is the hub of an industry-leading network for design, manufacturing and delivery of advanced RF products, antennas and payload systems. The Center of Excellence will focus on developing reconfigurable payloads and advancing satellite systems that many already rely on, from high-def television broadcasts to GPS transmissions and secure government communications.
http://www.lockheedmartin.com/us/ssc/rf-payload-centerofexcellence1.html

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