

**A Study into the Tradeoffs Between TDM / MF-SCPC and TDM / MF-TDMA
Transport Options to Support IP-Based Multimedia Applications Under
Different Load Conditions Within a Point-to-Multipoint Satellite Network**

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(ABSTRACT)

This thesis provides the reader with an overview of the many elements that are involved in geosynchronous satellite point-to-multipoint Internet Protocol (IP)-based multimedia communications design and also takes a deep dive into the analysis of a real-life scenario, using the TDM / MF-SCPC and TDM / MF-TDMA media access techniques.

This thesis starts with a discussion of satellite network topologies utilized within point-to-multipoint satellite communications followed by an overview of the satellite communications channel. A discussion on the intelligent and proper selection of modulation and coding follows. Descriptions and characteristics of the satellite access technologies chosen to be analyzed are next followed by a detailed description of Forward Error Correction (FEC) techniques and a discussion on network-wide tradeoffs so selecting different options.

The thesis then presents the results of a real-life scenario, investigating both TDM / MF-SCPC and TDM / MF-TDMA media access technique options, pointing out the tradeoffs brought to the forefront earlier in the study. The major takeaway is that there does not exist a one-size-fits-all solution that works for each and every scenario.

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1. Introduction

There are two main objectives of this thesis. The first is to provide the reader with an overview of the many elements that are involved in geosynchronous satellite point-to-multipoint Internet Protocol (IP)-based multimedia communications design. Tradeoffs of the selection of options within these areas, including Radio Frequency (RF) elements, media access elements and also IP elements, are addressed and discussed. The second objective is to provide a deep dive into the analysis of a real-life scenario, using the two most applicable (and therefore most common in commercial practice) solutions to bring to light these many elements:

- Time Division Multiplex (TDM) Multi-channel per Carrier (MCPC) outbound with Frequency Division Multiple Access (FDMA) or Multi-Frequency Single Channel per Carrier (MF-SCPC) inbound links
 - TDM / MF-SCPC

- Time Division Multiplex (TDM) Multi-channel per Carrier (MCPC) outbound with multiple Time Division Multiple Access (TDMA) inbound links
 - TDM / MF-TDMA

This thesis starts with a discussion of satellite network topologies utilized within point-to-multipoint satellite communications, namely mesh and star, and the reasons behind the selection of the latter for this study. Next, an overview of the satellite communications channel is provided. Within this overview, both satellite and earth station hardware is described. Also, the three main parameters that define, at a macro level, the satellite's performance, namely its

Effective Isotropic Radiated Power (EIRP), its Figure of Merit (G/T) and Satellite Flux Density (SFD) are discussed. A discussion on the intelligent and proper selection of modulation and coding follows. Of note, these topics are introduced to provide the proper background for this study but this thesis does not dive into the details of link budget calculations due to the fact that this topic is covered in great depth in a number of publications referenced within this document.

Descriptions and characteristics of the different satellite access technologies chosen to be analyzed are next, including MCPC, TDM, FDMA and TDMA. After this, a detailed description of Forward Error Correction (FEC) techniques is provided, building up from the concepts of convolutional code and block code theory up to Viterbi, Reed-Solomon, and Turbo Product Coding (TPC) techniques.

A discussion on network-wide tradeoffs, addressing the elements that must be considered when selecting the use of shared and individual carriers, including the selection of modulation and coding pairs, along with High Power Amplifier (HPA) and antenna size selection, follows.

Next, the two tools used for this research, one with an IP focus and one with an RF focus, are introduced and described. The first is an Excel-based IP sizing tool developed specifically for this study that takes into account data traffic characteristics to provide an overall Information Rate required per satellite channel. The second tool, LST-5, is the Intelsat link budget tool used to perform link budget calculations on the Intelsat global fleet of satellites. The IP traffic calculator is used to generate the proper inputs for the LST-5 link budget tool. While the proper best modulation and coding rate can be determined by balancing the total required allocated bandwidth with Power Equivalent Bandwidth (PEB), results for all modulation and coding rates are shown to allow comparison and contrast. The analysis teams the most common modulation

techniques (QPSK, 8PSK) used in practice for point-to-multipoint links with chosen antenna sizes and frequency (C-Band) along with the most common coding rates (0.66 for TDMA and 0.75 & 0.875 for TDM, MCPC and SCPC). Of note, it is the goal of this analysis to mirror, to the best possible, common practice and commercially available options. All parameters and calculations used within the IP sizing tool are then provided.

A description of the network characteristics considered follows, including the number of sites, the satellite under study (with parameters), the location of sites, hub and remote antenna sizes, along with the RF performance of the modems under study. After this, a presentation of the results is provided followed by a discussion of these results and conclusions. Lastly, a summary of suggested areas of further and additional research is provided.

2. Satellite Network Topologies

The two topologies leveraged within a point-to-multipoint satellite communications network are mesh and star.

2.1 Mesh Topology

A mesh topology provides a single-hop connection between each station to each other station on a network. (Hug) provides an excellent summary of the means by which remotes can communicate effectively with each other through the use of a single satellite hop. Figure 2.1 provides an illustration of these possible single-hop connections within a mesh satellite network.

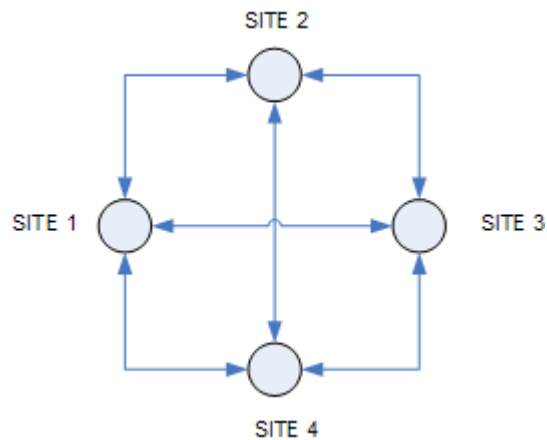


Figure 2.1. Mesh Topology

2.2. Star Topology

A star topology provides single-hop connectivity to each remote site from a central site, which is commonly referenced to as the “gateway” or “hub”. While remote to remote connections are possible, traffic between these two sites must traverse the satellite link twice, once from the remote to the hub, followed by a redirect back over the satellite to the destination remote. Figure 2.2 provides an illustration of the possible single-hop connections within a star satellite network.

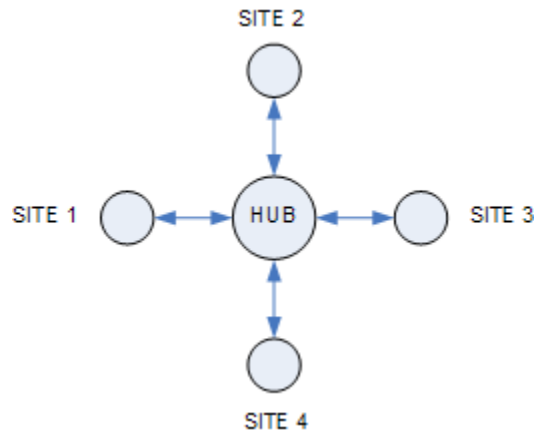


Figure 2.2. Star Topology

Due to the fact that the latency involved for each satellite link is approximately 250 milliseconds, caution must be taken when using double-hop connectivity to ensure that the mix of applications in use can handle the greater than the half second latency involved in the connection. While the any-to-any point connectivity that a mesh topology provides may seem

to be the best selection for any mix of traffic, the selection of the proper topology depends, according to (Mar), on the structure of information flow within the network, the requested link quality / capacity along with the allowed transmission time delay. In addition, the size of transmission equipment (antennas and amplifiers) required at each site must be considered because for any-to-any connections, the hardware at each site must be able to support the satellite link to the worst-case site in the network while ensuring the required availability and quality per a given Service Level Agreement (SLA). In general, if traffic will only flow from remotes to the hub, or if a small amount of traffic is to flow from remote to remote, a star topology is the best solution. For the traffic profiles to be addressed within this study, use of a star topology has been chosen.

3. Satellite Communications Overview

3.1 Satellite Hardware

The communication system of a satellite consists of two major elements, the antenna subsystem and the transponder subsystem. Detailed summaries of the exact makeup and functions of all on-board satellite hardware are provided in (Pra), (Sun), (Rod), (Gag) and (Mar).

Figure 3.1 provides a high-level overview of the major components of a satellite communication system.

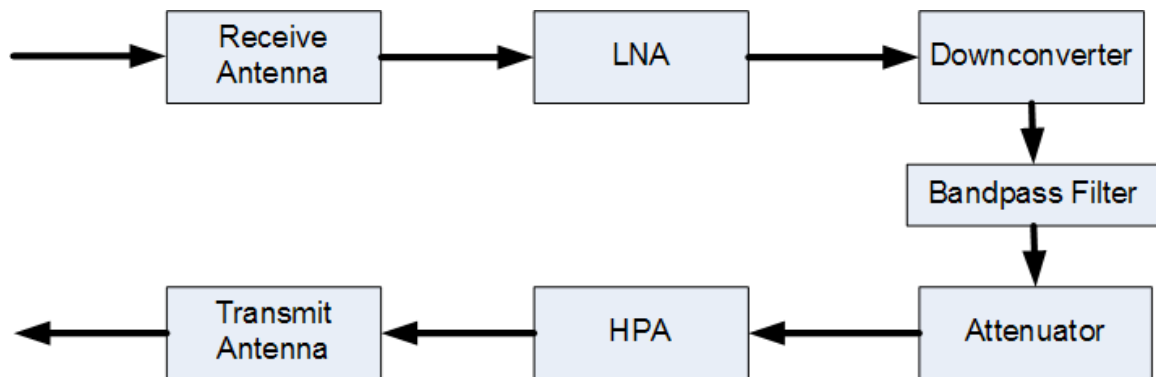


Figure 3.1. Satellite Communications On-Board System Elements

3.1.1. Antenna Subsystem

The antenna subsystem of a satellite consists of either a single feedhorn teamed with a shaped reflector or via a multi feed array teamed with a parabolic reflector. Both of these solutions act to shape the manner in which the available downlink power will cover the earth. When a single feedhorn is used, the reflector is constructed in a manner that allows its reflection of the transmitted signal to create the desired radiation pattern towards earth. Conversely, a multi-feed array consists of many small feedhorns that are each excited in the proper manner (with the proper power levels) to create the desired radiation pattern towards earth. In the commercial world, the satellite manufacturer works closely with the satellite operator to ensure that the proper levels of the finite amount of transmit power available falls to the desired geographic areas.

3.1.2. Transponder Subsystem

(Rod) and (Pra) describe a satellite transponder as the path through which a signal passes while traversing from the receive antenna (from earth) to the transmit antenna (to earth). It consists of a Low Noise Amplifier (LNA), one or two downconverters (and accompanying bandpass filter(s)), an on-board attenuator and an amplification element that consists of one or two amplifiers (HPAs). There are two types of HPAs that are used, Solid State Power Amplifiers (SSPAs) and Traveling Wave Tube Amplifiers (TWTAs). While SSPAs are smaller than TWTAs in terms of mass, they are less efficient and are not capable of providing as much power. When supporting a single carrier within a transponder, HPAs can be run near its full useable power (typically 40-65 Watts for C-Band and 140-150 Watts for Ku-Band TWTAs). However, when two or more than two carriers are being supported, TWTAs must be backed off

appropriately to ensure that unwanted harmonics are not unfairly amplified along with the desired proximity carrier, thereby creating distortion. Satellite operators must operate satellite HPAs at the proper power level (according to its non-linearity transfer characteristics) to minimize this distortion. The term transponder back-off is defined to be the point of maximum power at which the HPA can operate so as not to create distortion. TWTAs have non-linear characteristics that require the satellite operator to exercise caution when using them as they typically need to be backed-off more than SSPAs.

3.2. Satellite Performance Elements

3.2.1. Effective Isotropic Radiated Power (EIRP)

(Pra) The total transponder power is a function of the combination of the satellite's transmit antenna teamed with its TWTA and is defined as the Effective Isotropic Radiated Power (downlink EIRP) towards earth, measured in Decibel Watts (or dBW). Teaming the proper antenna design with the available power of the on-board TWTA creates the downlink EIRP pattern on earth that supports the entire bandwidth of the transponder, typically 36, 40 or 72 MHz. For example, let's reference IS-907 Satellite Spot 1 Beam, currently operating at 332.5 degrees East. Satellite operators work with satellite manufacturers during satellite design to clearly define these EIRP contour maps to ensure that the finite power resource available on the satellite is most efficiently and effectively used.

Power levels received from the satellite differ greatly and are dependent on the location of the downlink site. For instance, IS-907 has peak power of 53.0 dBW, which can be received

by earth stations within the shaded contour. Earth stations within this 53.0 dBW contour are said to be “advantaged”. Power levels fall off as geographical distances increase from beam center. For instance, earth stations that fall within the 45.0 dBW contour receive the signal from the satellite 8 dB lower than stations within the main contour. Earth stations that fall near beam edge are said to be “disadvantaged”.

3.2.2. Figure of Merit (G/T)

As an EIRP contour defines the downlink performance of a transponder, uplink performance is defined by a G/T contour. G/T defines the sensitivity of the satellite receive antenna in the direction from the transmitting terminal and is an important value as it determines the signal to noise ratio of the uplink. The G value represents the satellite receive antenna power gain, while T represents the system noise temperature. (Pra) provides an excellent description of this figure of merit and its importance in proper satellite link design. Since antenna gain is dimensionless while temperature is in Kelvins (K), this value is stated in dB/K, although this should not be interpreted as decibels per Kelvin (Rod). Let us consider the G/T plot for the Nilesat 102 Satellite, currently operating at 7.0 degrees West (Nil).

The sensitivities of the satellite receive antenna in the direction from transmitting terminal at different geographic locations differ greatly. For instance, the satellite is most sensitive in the five regions surrounded by the 1.5 dB/K contour while being less sensitive to signals being transmitted from the earth within the beam edge contours (falling to -6.0 dB/K at the beam’s edge). Disadvantaged earth stations that fall within the -6.0 dB/K contour must

transmit at a level 7.5 dB higher than those that are advantaged within maximum value contour to be received at the same level at the satellite.

3.2.3. Satellite Flux Density (SFD)

For geosynchronous satellites that remain station kept (defined as +/- 0.05 degrees East/West and North/South from its defined orbital slot) and do not operate in inclination, the given pair of clear-sky EIRP and G/T values remain static for a given latitude and longitude pair on earth. To ensure that the uplink signal is amplified to the proper level while traversing the transponder path, an on-board attenuator is utilized. This attenuation element is the single dynamic element that determines the resulting signal level required to be passed to the transmit HPA to ensure the received signal is received correctly at the earth station. (Gag) The parameter used in satellite communications to state this element is called the Satellite Flux Density (SFD) setting and is expressed in dBW/m² units.

For given EIRP and G/T contours, lowering a transponder's SFD setting on the satellite allows a remote station to transmit a lower powered signal to the satellite while still allowing transmission from the satellite back to earth at the same power level. This would be advantageous in cases when caution needs to be taken with uplink power levels or when smaller transmit equipment is required on the ground. Care must be taken, however, as decreasing this SFD value (therefore increasing its sensitivity) would render the satellite communications channel more susceptible to noise from the ground. There are tradeoffs to be considered in this case and while SFD settings on a satellite can be modified quickly, often in steps to allow level

setting on the ground, care must be taken and all factors must be considered before making these changes.

3.3 Earth Station Hardware

For earth stations that receive and transmit (versus a receive-only ground station), the transmit side hardware consists of a modulator that converts baseband data to an Intermediate Frequency (IF), an upconverter that converts the IF signal to the desired RF and an HPA (either TWTA or SSPA) that transmits the signal towards a reflecting antenna, which radiates the signal to the spacecraft. On the receive side of the link, there is a receive antenna, an LNA, which amplifies the desired signal from noise and a downconverter, which converts the signal back to baseband. Figure 3.4 provides an overview of transmit and receive earth station elements within an earth station system.

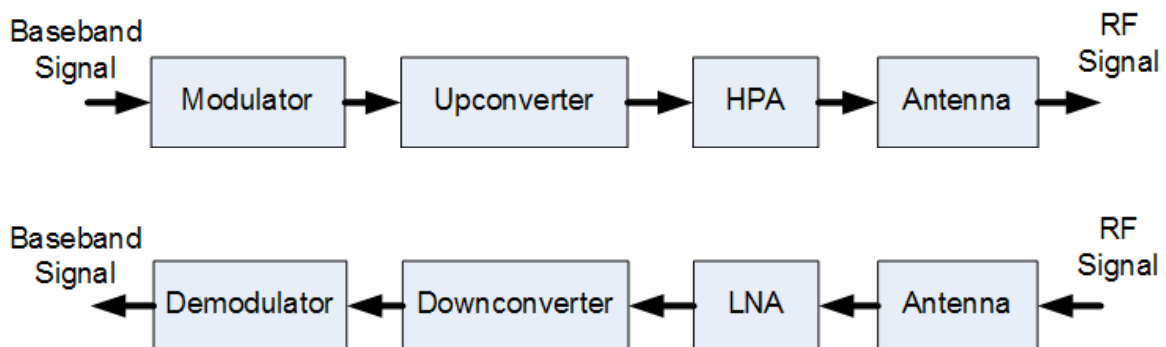


Figure 3.2 Transmit and Receive Earth Station Elements

3.3.1. Earth Station Antenna

As the main element in terms of cost and complexity, selection of the proper earth station antenna is essential. According to (Mar), the characteristics required for an earth station antenna are:

- High directivity in the direction of the nominal satellite position
- Low directivity in other directions in particular that of nearby satellites
- High antenna efficiency for both uplink and downlink frequencies
- High isolation between orthogonal polarizations
- Lowest possible antenna noise temperature
- Continuous pointing in the direction of the satellite

The most widely used antenna type in satellite communications is parabolic, most often in a direct feed reflector configuration with the feed horn located at the focus (Rod). The maximum gain of a parabolic antenna is expressed as (Pra):

$$G = (4 * \pi * A_r * \eta) / \lambda^2 \quad (3-1)$$

A_r = physical aperture area (m²)

η = antenna efficiency

λ = wavelength (m)

It can be seen from this equation that the gain of the antenna is proportional to its physical aperture area (proportional to the square of its radius). It is often assumed that due to this fact, the biggest antenna possible should always be chosen as it provides the largest receive and transmit gain on the ground along with greatest directivity. While an antenna's gain does indeed improve with increased size, there are two main drawbacks in the practicality of using large hardware to using a larger antenna in remote areas, which are the most likely locations for satellite communications as fiber and microwave build outs continue. The first disadvantage is the higher cost of a larger antenna versus a smaller unit. When taking into account a point-to-multipoint network with 10's, 100's or even 1000's of sites, this increased capital expenditure is multiplied quickly. Secondly, the ease of shipment and installation of an antenna are inversely proportional to the size. In other words, it costs more to ship and may require additional remote technicians to install a larger antenna in the field. Often, remote earth stations of point-to-multipoint satellite networks are in rural/remote areas, a fact that renders the delivery and installation of each antenna more difficult.

3.3.2. Earth Station Transmitter

Similar to a satellite transmitter, an HPA is used on the ground to transmit the communications signal. The selection of proper hardware is usually determined by the number of carriers from a remote site and the total power required, in Watts, to transmit the signal with the appropriate signal levels to be received by the geosynchronous spacecraft. When more than one carrier is transmitted from an earth station, at least 3 dB of backoff is required to minimize

the chances of intermodulation and/or driving the HPA into saturation. In commercial practice, either an SSPA or TWTA is selected when there is more than a single carrier and/or the link requires greater than 50 Watts of power to properly close the link. If less than 100 Watts of power is required, often a Block Upconverter (BUC) is utilized. The BUC gets its name due to the fact that it upconverts a selected “block” of frequencies from an intermediate frequency (often 70MHz or 140MHz) to the proper transmit frequency (typically C-Band or Ku-Band). Commercially available BUCs range from \$4,000 for a 10 Watt unit to \$12,000 for a 100 Watt unit. As with antennas, it is desirable to minimize the size of this transmitter to drive attractive economics. This is of particular concern when operating a point-to-multipoint network as each remote site must be equipped with these devices.

3.3.3. Proper Earth Station Hardware Selection

The vast difference in receive power levels from the same transponder on the same satellite, required transmit power levels to the same transponder on the same satellite, ability to provide attenuation to the transponder on-board the satellite are all elements that need to be taken into consideration when selecting the proper earth station hardware.

It will be shown in this study that different satellite communications access technologies require different mixes of antenna and HPA sizes and therefore require different capital expenditures at each remote site.

3.4. Proper Modulation and Coding

Each satellite carrier uses a fraction of a transponder's bandwidth and a fraction of its power, both of which are finite. When determining the total resource of a satellite transponder that must be allocated to a link, the greater of the occupied bandwidth and proportion of power is chosen. In the case when the required PEB is greater than the actual occupied bandwidth, a link is said to be Power Limited. In this case, a larger fraction of the power of the transponder is used than the fraction of bandwidth on that transponder. Conversely, in the case when the occupied bandwidth is greater than the PEB, a link is considered to be Bandwidth Limited. In this case, a larger fraction of the bandwidth of the transponder is used than the fraction of power of that transponder. Proper satellite link design selects the correct modulation and coding rate to equate allocated bandwidth with PEB.

3.4.1. Transponder Bandwidth

Bandwidth is allocated to a link in terms of the total Megahertz (MHz) required for the link. Determining the total bandwidth is a simple calculation:

$$BW = (\text{Information Rate} / m) / (k / n) \quad (3-2)$$

Information Rate = Datarate to be sent (Mbps)

k / n = FEC Code Rate

m = number of bits per symbol

Code Ratio = Information

For example within a 36MHz transponder, a 9Mbps link using QPSK (2 bits per symbol) and $\frac{3}{4}$ Turbo Code would require $(9 \text{ Mbps Information Rate}) / (2 \text{ Bits/Hz}) / (\frac{3}{4} \text{ Information Bits / Coded Bits}) = 6 \text{ MHz}$.

3.4.2 Transponder Power

Power is allocated to a link in terms of Power Equivalent Bandwidth (PEB). This calculation is much more complicated and explained in detail in (Rod), (Pra), (Sun) and (Mar). These sources provide the theory and details of proper link budget calculations and detail the many gains and losses along the satellite communication path.

As stated within these sources, a satellite transponder is defined by:

- Bandwidth
- Saturated ERIP
- Satellite Flux Density
- G/T Figure
- Output Backoff or attenuation
- Input Backoff or attenuation

In general, in addition to the transponder elements stated above, the main determinants of a satellite communications link are:

- Latitude and longitude of spacecraft
- Latitude and longitude of uplink and downlink earth stations
- Uplink and downlink antenna sizes
- Uplink and downlink antenna efficiencies
- Uplink and downlink frequencies
- Uplink and downlink transmit and receive gains (at proper frequencies)

The two elements that are used to determine the proper satellite resource required to support the link are the planned information rate of the link and the minimum Energy per Bit (E_b) to the Spectral Noise Density (N_0) (E_b/N_0) for the required Bit Error Rate (BER) to meet a stated SLA. The required E_b/N_0 at a remote site varies depending upon the modulation, coding method and coding rate to be used. In general, the more aggressive the modulation and coding, the more efficient, in terms of Megabits (Mbps) per MHz, the link is. While higher order modulations (16-APSK, 16-QAM, 32-APSK, 32-QAM) provide an increased number of bits per symbol (thereby increasing spectral efficiency), the resulting symbol state distance requires a higher E_b/N_0 ratio at the receive side of the link to allow the decoder to properly receive the intended transmitted data and ensure the required BER. The result of an increased required E_b/N_0 at the demodulator of the receiving station is a higher PEB requirement.

4. Medium Access Techniques

The satellite medium access method utilized within point-to-multipoint Very Small Aperture Terminal (VSAT) networks depends on the direction of the traffic, either from hub to remotes (outbound link) or from remotes to hub (inbound link). Typically, a single shared transport is used in the outbound direction that leverages a mechanism that allows traffic destined to different remotes to be allocated bandwidth either statically or dynamically. For the inbound link(s), either shared or multiple dedicated links are utilized to allow traffic to be transported to the central location.

4.1 Outbound Link

4.1.1. Multichannel per Carrier (MCPC)

(Rod) In a point-to-multipoint topology, a single Multi Channel per Carrier (MCPC) signal is transmitted from the hub station, which provides a broadcast facility to a number of remote stations with each VSAT accessing the satellite in some form of multiple access mode. An MCPC link carries multiple signals, allocating bandwidth on an as-needed basis, determined by pre-defined policies, to different sites within a network. (Rod) There are two types of MCPC links used in satellite communications, Time Division Multiplex (TDM) and Time Division Multiple Access (TDMA). Both provide the means to share bandwidth to remote sites. Any shared mechanism will require more overhead due to both the requirement of addressing information along with timeslot allocation, than a dedicated method.

4.1.2. Time Division Multiplex (TDM)

A TDM link allocates bandwidth from a single source to channels that may be destined for different (or multiple) remote sites. In point-to-multipoint environments, this access technique is most commonly used on the outbound link. Figure 4.1 provides an overview of a TDM data stream.

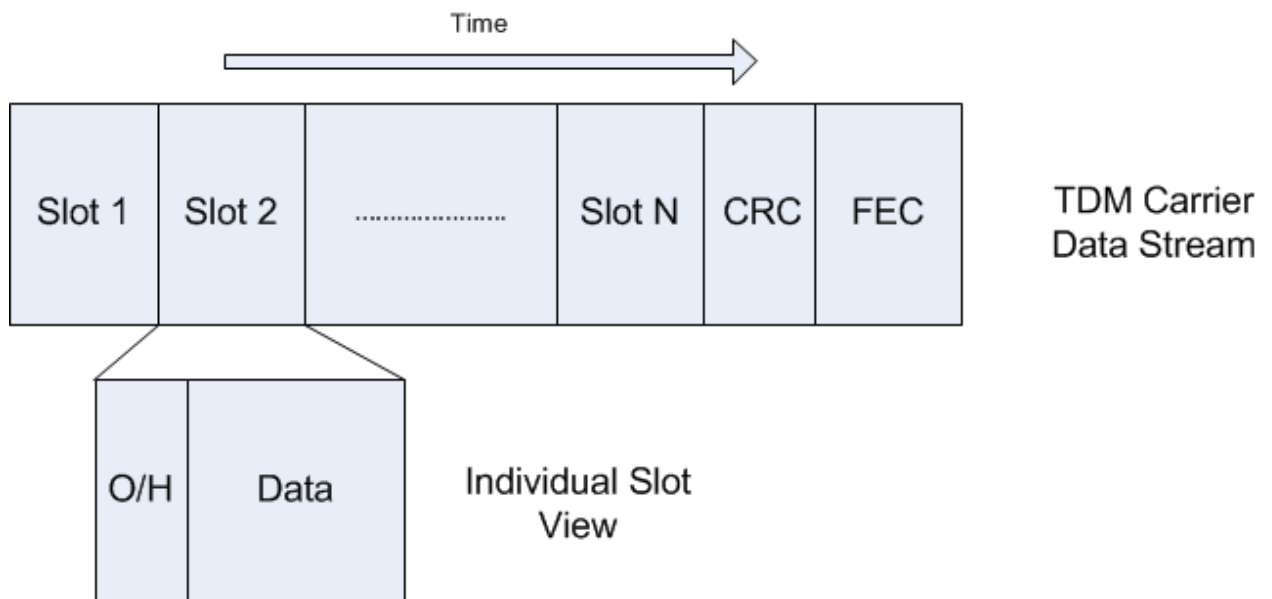


Figure 4.1. TDM Data Stream

As can be seen in Figure 4.1, each slot is assigned to a single remote site, which carries within it the proper overhead (including source/destination addressing) plus data. At the end of each block is the Cyclic Redundancy Check (CRC) and FEC data.

In a packet-switched environment, timeslots need not be assigned permanently to streams but rather can be shared on an as-needed basis. TDM, created to operate within a circuit-switched environment, sets up a link for a single communications path between two sites and allocates a static amount of bandwidth to the link, whether the communications channel requires the bandwidth or not. With permanent assignment, each stream is allocated bandwidth periodically, whether the stream has content to send or not. In the case when no content is present, the slots will go unused, transmitting empty information. By allowing the sharing of timeslots, the total number of empty slots can be minimized and the total efficiencies can be maximized.

While the term “TDM” has been used in IP satellite communication literature, the actual implementation on outbound carrier is a form of “Dynamic TDM” in which timeslots are shared across remotes dynamically. Another way to reference this is as an “IP Packet-Switched Network over an MCPC signal”.

When determining proper satellite network design, it is essential to differentiate IP Rate from Information Rate. The IP Rate is defined as the total amount of actual IP data to be sent over the satellite link. In Figure 4.1, this can be determined by summing the total number of bits within the Data portion of Slots 1 through N. This is the usable data rate of any satellite link. The Information Rate is defined as the IP Rate plus the overheads within each slot. The total

efficiency of the link, not taking into account CRC or FEC information, can be determined by dividing IP Rate by Information Rate.

In TDM networks, because the traffic controller of the network lies at the hub and therefore decisions can be made on the fly before transmission over the satellite, TDM carriers achieve 98-99% efficiencies in terms of IP Rate vs. Information Rate.

4.2. Inbound Link

A comprehensive summary of methods used for inbound access is provided in (Ran) and include Frequency Division Multiple Access (FDMA), which allows the use of comparatively low-power VSAT terminals, and Time Division Multiple Access (TDMA), which allows the sharing of bandwidth at the expense of higher-powered (and more expensive) equipment.

4.2.1 Frequency Division Multiple Access (FDMA)

A Frequency Division Multiple Access (FDMA) link provides “always on” unrestricted bandwidth to a channel via a Single Channel per Carrier (SCPC) carrier. An SCPC link carries a single signal, allocating all of the bandwidth available at all times to this single carrier. This guaranteed bandwidth availability is a key advantage to the SCPC access mechanism. SCPC links are most frequently used for point to point links, connecting two sites to each other. In this case, links require little overhead as the receive station can only receive from a single station and therefore no addressing information is required to distinguish from which station the data is sent. Also, since all data is organized on the ground without the need for coordination or

timing, additional timeslots within the data stream are not required. The major disadvantage of SCPC is the fact that, within a network scenario with many sites, bandwidth cannot be shared amongst remotes. In other words, bandwidth is always available, even at times when a transmit station doesn't have data to send.

4.2.2. Time Division Multiple Access (TDMA)

A TDMA link dynamically allocates bandwidth from multiple sources to channels that may be destined for different (or multiple) remote sites. Figure 4.2 provides an overview of a TDMA data stream.

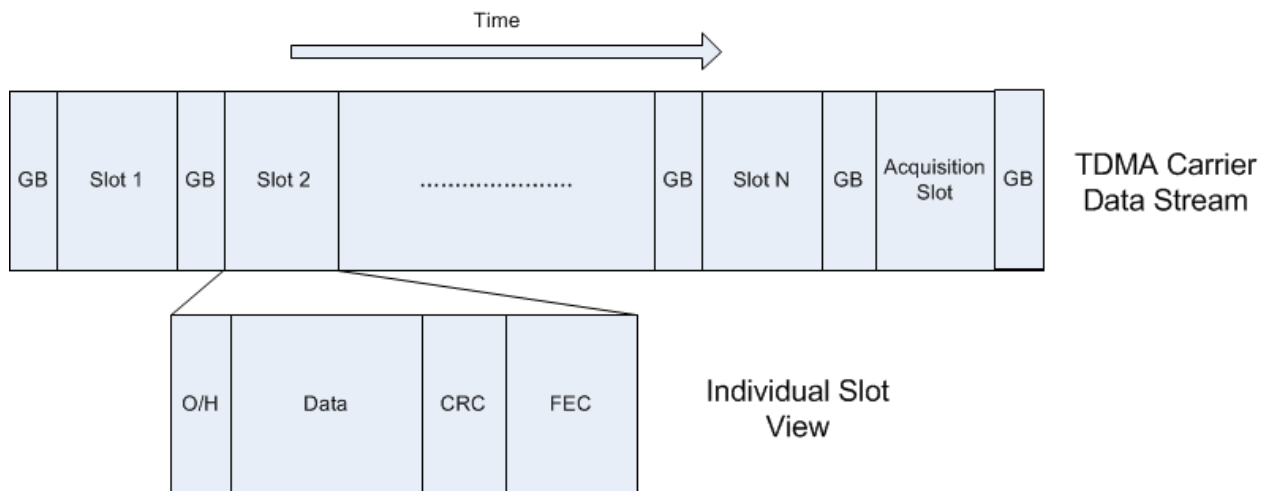


Figure 4.2. TDMA Data Stream

As can be seen in Figure 4.2, similar to with TDM, each slot is assigned to a single remote site, which carries within it the proper overhead (including source addressing) plus data. In the case of TDMA, since a different site transmits within each slot, and no two remotes can share a slot, each site must append its own CRC and FEC information to ensure valid reception. This is unlike a TDM channel, which can leverage larger block sizes, and therefore provide higher efficiencies. Additionally, because the remote sites accessing the satellite medium are geographically disperse and therefore not the exact same distance from the satellite, a guard time is needed to allow their transmitted signal from earth to the satellite to be received, retransmitted to the ground and received by the downlink station. Without such a guard time, bursting signals from remotes would overlap when they reach the spacecraft, thereby creating interference.

The Overhead (O/H) portion of each slot consists of:

- Demand Header
- Link Layer Header
- Pad Header

Since each remote must continue to report its bandwidth demands to the hub location, there need to be a mechanism in which this information is transported along with data flow. The Demand Header consists of this information and also other Quality of Service (QoS) related information, which is used at the hub location to properly process received data and convert back to valid IP packets, with proper priority.

The Link Layer Header is the portion of the data flow that maintains a reliable stream over which all Transmission Control Protocol (TCP) traffic is sent and possibly retransmitted if there are dropped packets. The Link Layer protocol header contains information that uniquely identifies this remote to the hub side.

The Pad Header is due to TDMA packing. Packing pulls in individual packets into TDMA bursts. To make efficient use of all available TDMA bandwidth, the packing layer potentially holds onto partially filled bursts in an attempt to fill them completely (with subsequently arriving packets). This typically adds 1-3 bytes of header to each TDMA burst.

As with TDM, when determining proper satellite network design for TDMA links, it is essential to differentiate IP Rate from Information Rate. In Figure 4.2, the IP Rate can be determined by summing the total number of bits within the Data portion of Slots 1 through N, similar to TDM. However, unlike TDM, where the Information Rate is defined as the IP Rate plus the small overheads within each slot, the Information Rate of a TDMA link must also include Guard Bands between each slot (N of them) and the Acquisition Slot. Once again, the total efficiency of the link, not taking into account CRC or FEC information, can be determined by dividing IP Rate by Information Rate. Depending upon the dynamic allocation method used, TDMA carriers typically achieve 60-93% efficiencies in terms of IP Rate vs. Information Rate.

(Rod) A form of Demand Assigned Multiple Access (DAMA) is employed in most systems in which channel capacity is assigned on an as-needed basis. The problem, as described in detail in (Abr), of access shifts to how remotes in the network may reserve the channel in an efficient and equitable manner. (Abr) described a method of utilizing a Code-Division Multiple Access (CDMA) method using spread spectrum techniques, teamed with the aloha protocol.

While this method is an efficient option for multiple access, it is best suited for low throughput, bursty data transfers due to the random access of the aloha protocol. Multimedia traffic, which includes not only data but also voice and video traffic, carries with a requirement of increased bandwidth accessibility along with a higher duty cycle than the CDMA aloha method provides. To meet the requirements of a multimedia traffic mix, bandwidth must be provided with a dedicated rate not available within a CDMA aloha environment along with the ability to request additional bandwidth as required. When additional bandwidth above the minimum allocated is required, a remote must request this bandwidth within the shared TDMA channel. To accommodate these requests, an Acquisition Slot is required to allow remotes that have data to transmit to request bandwidth during the next frame. This acquisition slot is shown in Figure 4.2 and is included in the additional overhead required for a TDMA channel.

(Ran) provides a comprehensive summary of a number of methods in use today, many of them proprietary, with the most common access methods being FDMA and TDMA.

5. Forward Error Correction (FEC)

5.1. The Need for Forward Error Correction

Due to the very noisy environment of satellite communications, forward error correction plays a key role in ensuring that data is received correctly at the remote end of a link. Forward error correction involves the addition of redundancy to a message before transmission to allow a bit pattern that incurs errors along during transmission to be properly decoded back to the original data stream. This excess amount of information sent over the satellite acts as overhead, albeit a necessary overhead to ensure the integrity of the data. It is the end goal of any satellite engineering exercise to minimize this overhead while still maintaining a minimum performance level in terms of accuracy of data.

The required performance of error correction within a noisy link is a function of BER vs. E_b/N_0 . BER is defined as the number of received bit errors divided by the total number of transferred bits. Most bit errors are caused by noise and/or interference in the communications system and the probability that a bit is received in error is defined as the bit error probability (p_e).

E_b is the total energy per bit received at the remote site location and is expressed in Joules. (Rod) The available noise power from a thermal noise source is stated as:

$$P_N = k \cdot T_N \cdot B_N \text{ Watts} \quad (5-1)$$

$$k = 1.38 \times 10^{-23} \text{ (J/K)} = \text{Boltzman's constant}$$

TN = equivalent noise temperature (K)

BN = equivalent noise bandwidth (Hz)

(Rod) The noise power per unit bandwidth is termed the noise power spectral density and is denoted

$$N_0 = P_N / B_N = k * T_N \text{ Joules} \quad (5-2)$$

E_b/N_0 is the measure of signal to noise ratio for a digital communication system and is closely related to carrier-to-noise ratio (C/N) in the following manner

$$E_b/N_0 = C/N * (B/f_b) \quad (5-3)$$

B = channel bandwidth (Hz)

f_b = is the channel data rate (bps)

Also, E_b/N_0 can be viewed as a normalized measure of Energy per Symbol per Noise Power Spectral Density (E_s/N_0)

$$E_b/N_0 = E_s/N_0 / \log_2(m) \quad (5-4)$$

m = number of bits per symbol

5.2. The Shannon Limit

(Aha) There exists a theoretical limit to any FEC code's ability to correct a corrupted data stream known as the Shannon Limit. The Shannon Limit defines the optimum theoretical

boundary for a given code rate and, as any link performance measure can be characterized, is a function of BER vs. E_b/N_0 .

(Aha) The Shannon Limit for binary input channels is depicted graphically in Figure 5.1.

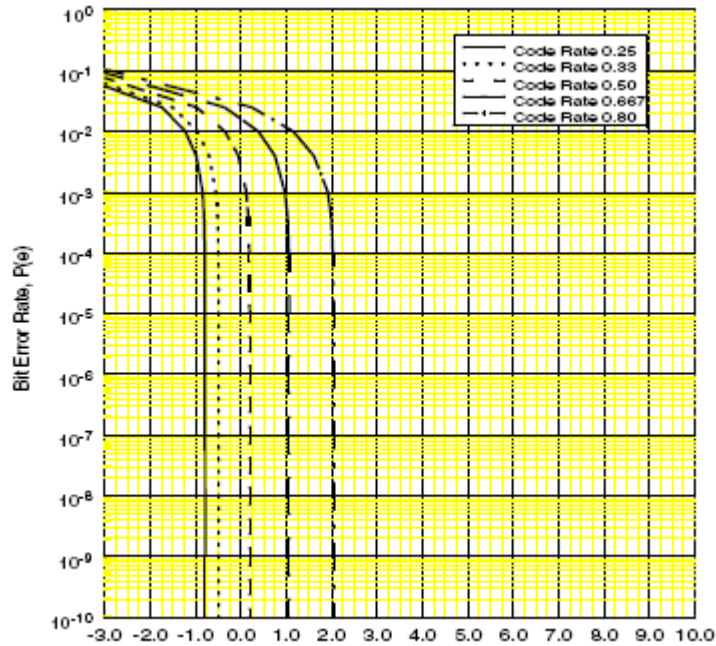


Figure 5.1. Shannon Limits for Varying Code Rates

(Aha) This determines the lower bound for E_b/N_0 that can be recovered using a perfect error correction code. No error correction code can perform better than the Shannon Limit and as a code approaches this limit its complexity and code block size increases exponentially.

Figure 5.1 shows the concept that for lower code rates, the lower the required limit on E_b/N_0 for a given BER. Code rates of 0.25 to 0.80 are shown. The code that performs the closest to the Shannon Limit out of all available codes provides the user with the highest value.

(Sun) Figure 5.2 provides an overview of the different elements of a satellite link, including the Forward Error Correction element of encoding and decoding of data.

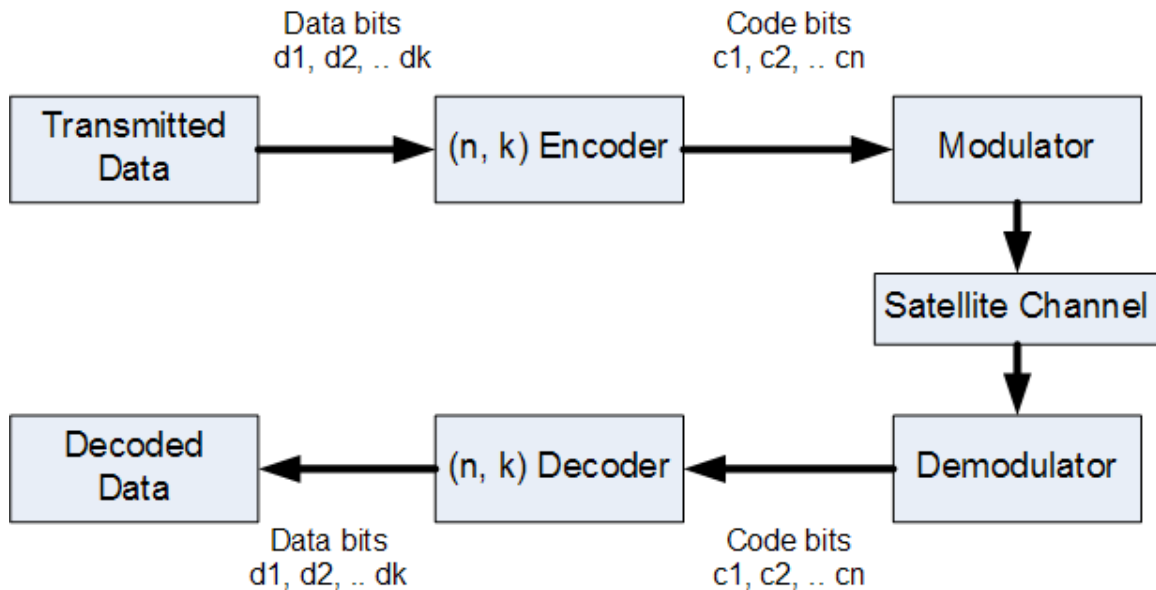


Figure 5.2. Satellite Link Overview (Forward Error Correction Focus)

On the transmit side of the satellite link, data bits are fed into the encoder, which uses an algorithm to add the proper redundancy to the data to allow errors to be detectable. This code stream, C , is passed to the modulator, which converts the baseband signal to the RF frequency to be used on the satellite link (perhaps using an IF frequency as a first step). The signal is then transmitted to the geosynchronous satellite, which receives the signal, amplifies the signal and re-transmits the same signal back to earth, in the direction of the receive earth station. As many sources of noise are present in the long-distance link, the demodulator on the

receive side of the satellite link receives an altered signal, demodulates the signal from RF to baseband and passes this received data stream onto the decoder, which uses an algorithm to determine, to the best of its abilities, the intended transmitted data.

5.3. Forward Error Correction Techniques

5.3.1. Parity Codes

In their earliest form, commonly used FEC techniques used parity to determine if errors have occurred in transmission. Parity is determined by counting the number of ones in a unit of data and if the number is odd, then the data string is said to have odd parity. Conversely, if the number of ones is even, then the string is said to have even parity. A parity bit is added to the data string with this bit being set to 0 for even parity and 1 for odd parity. For example, 10101 is a 5-bit data unit that contains three ones so the parity bit in the transmitted data string would be a 1. To calculate even parity, the XOR operator can be used and for odd parity, the XNOR operator can be used.

The use of a single parity bit, while incorporating minimal overhead, unfortunately is not very robust or reliable since if the parity bit is 0, it is assumed that no errors were experienced while in reality, either 0 or 2 (or any even number of) errors have occurred in transmission. Likewise, any odd number of errors that occur would result in the same received parity bit setting of 1. To make matters worse, even if the exact number of errors is determined, it is not possible bit a single parity bit to determine the exact location of the error. Obviously, more powerful mechanisms were needed to ensure data integrity while minimizing overhead.

There are many different types of FEC codes in use today for satellite communications but each has its basis in either block coding concepts or convolutional coding. At times, two codes are used in conjunction via concatenation.

5.3.2. Block Codes

A block code is a memory-less code that maps k input binary signals to n output binary signals. (Wic) Figure 5.3 provides an overview of block coding.

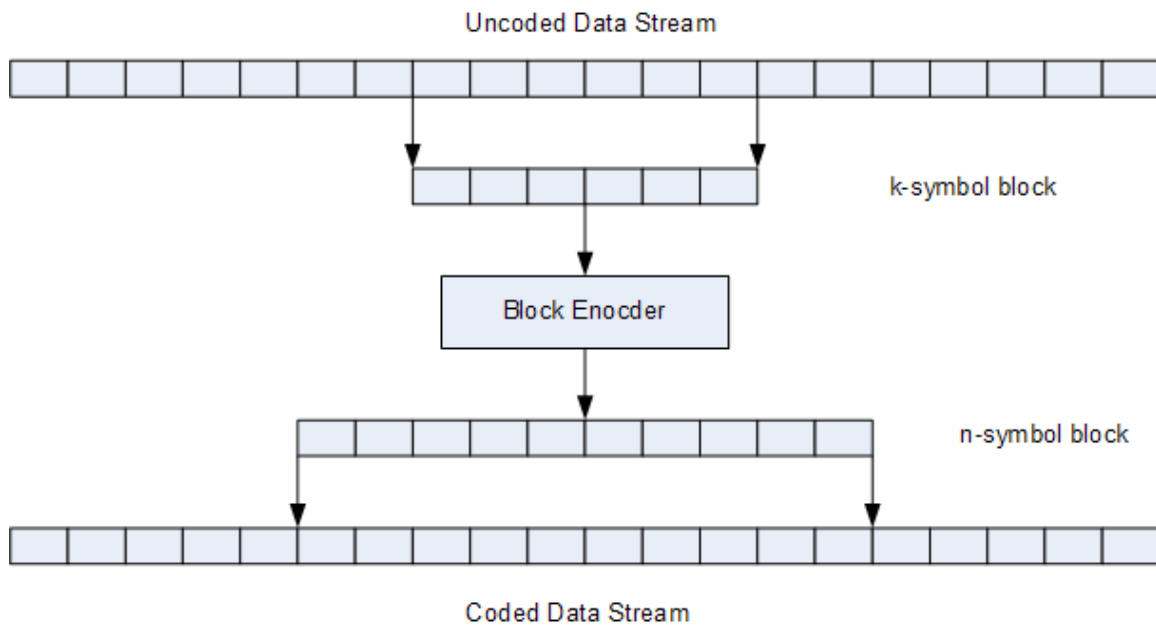


Figure 5.3. Block Coding Overview

The block encoder accepts a set of k bits, performs the proper encoding mechanism on the data string and outputs n bits that are placed into the coded data stream. In this manner, a single bit is used in a single operation and passed into the coded data stream to be transmitted over the satellite link. On the receive side, the block decoder attempts to determine the original data sequence by performing the reverse process.

5.3.2.1 Hamming Codes

(Ham) R. W. Hamming, considered by many as the founder of the subject of error control coding, developed the first major class of linear binary codes designed for error correction. Their first application was in the world of long-distance telephony. Hamming took the concept of simple parity check to the next level, being able to find the exact location of one or more errors within a transmitted data string. Hamming determined that using matrix calculations, using parity check matrices, would force different locations of the incorrect bit to produce different error results. In other words, not only was the occurrence of an error determined, but also its location in the data string. For example, for a 7-bit message, there are seven possible single bit errors so three error control bits could be used to specify if an error occurred and if so, which bit was in error.

(Ham) In particular, a Hamming code has the following parameters:

- Block length is $n = 2^m - 1$
- Number of message bits is $k = 2^m - m - 1$
- Number of parity bits is $m = n - k$

- d_{min} is 3
- Error correcting capability is 1
- $m \geq 2$

Figure 5.4 shows the makeup of a (7,4) Hamming Code.

D D D D P P P

Figure 5.4. Makeup of a (7,4) Hamming Code

Each D bit shown represents a data bit while each P bit shown represents a parity bit. The parity bits are calculated based upon the makeup of the data bits. It can be seen that this code word contains seven total bits, four of which represent actual data and three of which represent parity information.

Hamming codes also introduced the error correction community to the concept of matrix multiplication. Hamming codes utilize a generator matrix, which creates a code word that is sent through the link. Figure 5.5 provides an example of a generator matrix, G , for a (7,4) Hamming code.

$$\left\{ \begin{array}{ccccccc} 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 \end{array} \right\}$$

Figure 5.5 Generator Matrix for a (7,4) Hamming Code

This generator matrix, G , is multiplied by the data stream, p , to create the codeword, x , which is sent over the link. When this codeword is received on the receive end of the link, possibly with errors, it is multiplied by the parity check matrix H , to create a syndrome vector. Figure 5.6 provides an example of a parity check matrix, H , for a (7,4) Hamming code.

$$\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{array} \right\}$$

1 1 1

Figure 5.6 Parity Check Matrix for a (7,4) Hamming Code

(Wic) If the syndrome vector, which is independent of the transmitted codeword, is zero then no errors were experienced in transit. It should be noted that all of the vectors in a given row of a standard array must have the same syndrome, for the difference between any pair of vectors in a row is a code word. If the syndrome vector is non-zero, then the syndrome decoding table is used to find the exact location of the correctable error.

While this report will not dive further into the details of Hamming codes, (Wicker (Wic) provides much detail on their theory and design) it is important to reference them as Hamming's work moved the error correction community forward substantially and introduced nomenclature and methods that are still in use today. His work introduced the community to the naming convention of a block code as (n, k) with n equal to the total number of bits within a block and k the total number of data bits within that block. The total number of redundant bits is calculated by subtracting k from n , or $n-k$. Viewed another way, the code rate of any block code is defined as k/n . The higher the code rate, the less redundancy is included in the coded data stream, the lower the code rate, the more redundancy is included in the coded data stream.

Also, two important definitions were created from his work. (Wic) The Hamming distance between two blocks is defined as the number of coordinates in which the two blocks differ. This value allows for a useful characterization of the error detection and error correction capabilities of a block code as a function of the code's minimum distance, which is defined as the minimum Hamming distance between all distinct pairs of code words in the code stream C .

While Hamming codes were not in themselves very powerful by today's standards, only allowing the correction of a single bit error, the concept of detecting multiple bit errors teamed

with the idea of overlapping parity bits so they did not only check the data being transmitted but also each other was key to later findings. Hamming's work moved the error correction community, and the satellite communications community in particular, forward to maximize code rates while increasing minimum distances. They also became a key ingredient of Turbo codes that were developed later that took the satellite industry closer to the Shannon Limit.

5.3.2.2 Extended Hamming Codes

(Wic) Extended Hamming codes are formed by adding a row of ones and a column vector of all zeroes followed by a one to the parity-check matrix for a Hamming code. In particular, an Extended Hamming code has the following parameters:

- Block length is $n = 2^m$
- Number of message bits is $k = 2^m - m - 1$
- Number of parity bits is $m = n - k + 1$
- d_{\min} is 4
- Error correcting capability is 1
- $m \geq 2$

Figure 5.7 shows the makeup of a (8,4) Extended Hamming Code.

D D D D P P P P

Figure 5.7. Makeup of a (8,4) Extended Hamming Code

Similar to standard Hamming codes (Figure 5.4 above), each D bit shown represents a data bit while each P bit shown represents a parity bit. The parity bits are calculated based upon the makeup of the data bits. While the last bit adds additional redundancy to the data stream, thereby decreasing the code rate (k/n), it increases the value of d_{min} from three to four, which significantly increases its error detection capabilities. It can be seen that this code word contains eight total bits, four of which represent actual data and four of which represent parity information.

5.3.2.3. Cyclic Codes

Linear cyclic codes are a subset of linear block codes. Two examples of cyclic codes used frequently in satellite communications are Bose-Chaudhuri-Hocquenghem (BCH) codes and Reed-Solomon (RS) codes.

(Wic) The fundamental work on BCH codes was conducted by two independent research teams. Binary BCH codes were discussed as “a generalization of Hamming’s work” by A. Hocquenghem (Hoc) in 1959 and also by Bose and Ray-Chaudhuri (Bos) in 1960.

(Sun) The Bose-Chaudhuri-Hocquenghem (BCH) code is a class of linear block code with the parameters:

- Block length is $n = 2^m - 1$
- Number of message bits is $k \geq (n - mt)$
- Minimum distance is $d_{\min} \geq 2t + 1$
- m is any integer
- $t = (2^m - 1)/2$ is maximum number of detectable errors

(Pet) Peterson proved that BCH codes were cyclic and also provided an efficient decoding algorithm and (Gor) Gorenstein and Zierler then extended BCH codes to arbitrary fields of size p^m .

(Aha) The Reed-Solomon block codes were developed in 1960 by I. Reed and G. Solomon in their June 1960 paper (Ree). This paper discussed an extremely powerful set of nonbinary codes that are closely related to BCH codes. (Gor) In fact, Gorenstein and Zierler described RS codes as non-binary BCH codes.

(Sun) The Reed-Solomon (RS) code is a subclass of non-binary BCH codes. An RS coder is (n,k) is used to code m bit symbols into blocks consisting of $n = (2^m - 1)$ symbols = $m(2^m - 1)$ bits. A t -error correcting RS code has the parameters of:

- Block length is $n = 2^m - 1$
- Number of message bits is $k \geq (n - mt)$
- Parity check size is $(n - k) = 2t$ symbols
- Minimum distance is $d_{min} \geq 2t + 1$ symbols

BCH and Reed Solomon codes were widely used in satellite communications due to their abilities to remedy burst errors, which were the most common in satellite communications. In fact, the Digital Video Broadcast (DVB) leveraged Reed Solomon coding in its first DVB standard for satellite communications. In particular, DVB uses Reed Solomon coding configured with 188 information symbols and 16 check symbols, which results in a total block size of 204.

5.3.3. Trellis/Convolutional

The second major class of error correction coding is trellis, also known as convolutional, coding. (Sun) Trellis codes use memory by remembering $(K-1)$ input signals immediately preceding the target block of L input signals. These $(K-1) + L = (K + L - 1)$ input binary signals are used in the generation of $n[(K - 1) + L]$ output binary signals corresponding to L input signals. Therefore the code rate is $L / [n(K + L - 1)]$.

(Sun) Convolutional coding is a subset of trellis codes. The convolutional encoder can be associated to a finite state machine storing $(k-1)$ message bits. At time j , the portion of the message sequence contains the most recent k bits. A convolutional decoder takes into account such memory when trying to estimate the most likely sequence of data that produce the received sequence of code bits. This is called maximum likelihood method for decoding convolutional codes. In 1967, Andrew Viterbi (Vit) developed a technique of decoding convolutional codes using this method that has since become the standard for decoding convolutional codes. Before we cover Viterbi decoding, a discussion on the different methods of decision decoding is required.

5.3.4. Viterbi Decoding

(Gag) An alternative to the block error-correction coding is the use of convolutional coding. Convolutional coding is another technique for encoding data bits into transmission chips, such that subsequent chip decoding leads to improved bit decoding. Rather than coding fixed-data blocks into fixed-chip blocks, each chip is generated instead through a continuous convolution of previous data bits. This convolution leads again to improved performance when operating at the same code rate. Decoding is achieved by detecting one bit at a time in sequence, based on the processing of sliding sequences of received chips. (Vit) The optimal decoding is obtained by means of a Viterbi decoding algorithm. (Aha) A Viterbi decoder receives soft information from the demodulator and outputs hard decision data. The decoder can use the soft information to determine if a given bit is a solid one or solid zero and outputs this hard decision.

5.3.5. Hard vs. Soft Decision Decoding

(Aha) There are two categories of decoding, hard decision decoding and soft decision decoding. In hard decision decoding, each received bit is given a value of one or zero depending strictly on whether the received data is higher or lower than a set threshold. Soft decision decoding includes not only a binary value of one or zero but also a confidence value associated with the given bit. In satellite communications, the decoder receives either hard or soft decision input from the demodulator and outputs either hard or soft decision data.

(Aha) To find and correct errors in the hard decision method, the decoder can use only the redundancy added by the encoder on the transmit end. The desired output of the decoder is a corrected codeword. Conversely, in the soft decision scenario, the decoder can leverage confidence levels along with the bit value decision passed to it from the demodulator to make the correct decision.

5.3.6. Concatenated Codes

(Sun) Linear block coders are more effective to correct burst of errors while convolutional coders are more effective on random errors. Convolutional coders can produce burst errors if there are too many random errors. In 1974, Joseph Odenwalder combined these two coding techniques to form a concatenated code. (Sun) A block code is used as internal code first, then a convolutional code follows second as external code for encoding; on decoding,

external convolutional code follows first, then the internal block code follows second.

Performance can be further enhanced if interleaving techniques between the two coding stages mitigate any burst that might be too long for the block code to deal with effectively.

Until the introduction of turbo coding, the most widely used satellite communications solutions concatenated Viterbi codes with Reed-Solomon codes to provide an improvement over stand-alone Reed-Solomon codes in terms of BER performance. The main reason was due to Viterbi decoders' tendency to produce errors in short bursts, which are easily correctable using Reed-Solomon codes. In fact, Intelsat made the teaming of an outer RS codec with a Viterbi decoder popular when it made this an Intelsat standard in the early 1990s due to its significant improvements in error performance with very little bandwidth expansion (typically < 10%). Interleaving is required in this combination scenario since RS codes are limited in how well they can correct errors that occur in bursts and these are exactly the types of errors that Viterbi decoder produce. Interleaving spreads out a burst of errors over a number of interleaving frames.

5.3.7. Turbo Coding

All of the concepts mentioned within this section moved the error correction community forward significantly and allowed a concept called "turbo coding" to be envisioned, developed and accepted as the industry standard. (Ber1) The concept of turbo coding was introduced by Berrou, Glavieux and Thitimajshima in 1993 in their paper "Near Shannon Limit Error-correcting Coding and Decoding: Turbo-codes", which was published in the Proceedings of IEEE International Communications Conference. Turbo coding leverages the advantages of soft

decision and iterative decoding concepts. There are two types of turbo coding, turbo convolutional coding (TCC) and turbo product coding (TPC).

Turbo convolutional coding, which is the focus within the seminal paper by Berrou, Glavieux and Thitimajshima, and also a follow-on paper by the former two (Ber2) entitled “Near Optimum Error Correction Coding and Decoding: Turbo-Codes”, utilizes convolutional codes and utilizes two recursive convolutional encoders (RCE) interconnected via an interleaver with a feedback decoding rule. Since the introduction of Turbo convolutional coding, there have been many instantiations of TCCs developed yet there have been few integrated circuits made available to the general commercial market that implement TCCs. The main reason for this is the complexity involved in using TCCs at high code rates which would require an extremely complex and powerful decoder. (Aha) Also, the performance of various TCCs have shown a significant error floor of approximately 10^{-5} , compared to significantly lower error floors with TPCs (the main reason for this minimal error floor for TPCs is due to their very high d_{min} values, which will be discussed later in this study). (Aha) Other advantages of TPCs over TCCs include the fact that TPCs function much better at higher data rates and require lower transmit power for a given performance value. Last, but certainly not least, TCCs are licensed by France Telecom while the concept and instantiations of TPCs are public domain, which has significantly increase the rate of their adoption in industry.

5.3.7.1. Turbo Product Code (TPC) Intro

A TPC is a multi-dimensional array of block codes. TPCs utilize constituent codes, usually Extended Hamming Codes or parity codes, used in serial to increase the power of their error detecting and error correcting capabilities.

Recall that the error correcting capabilities of any code is:

- $t = (d_{\min} - 1) / 2$

In general, it is attractive to maximize the value of d_{\min} as this value determines the error correcting performance. The resulting d_{\min} value of a multi-dimensional code is the result of multiplying each of the individual constituent codes together. If a known one-dimensional code has a d_{\min} value of 4, then a TPC that uses that same code in two dimensions would have a d_{\min} value of 16 ($= 4 \times 4$) and in three dimensions would have a d_{\min} value of 64 ($= 4 \times 4 \times 4$). Of course, the added error correction capability of a multidimensional code is countered by the additional overhead required due to the multiple dimensions. The advancement in error correction must be weighed with the increase in bandwidth required to transmit the given set of data.

Using a Soft In / Soft Out (SISO) decoder, soft decision data is fed into a SISO decoder. The output of this decoder is passed back into the same (or different decoder) which this process repeated a number of times until a confident solution is reached. Figure 5.8 provides an overview of this concept.

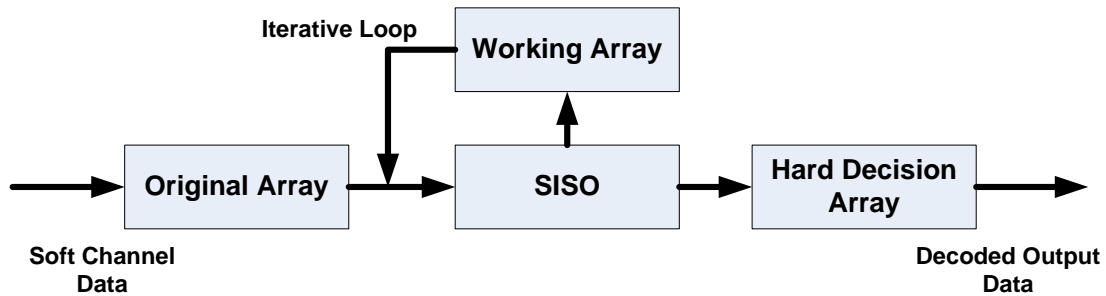


Figure 5.8. Turbo Decoding Concept Diagram

(Aha) To be effective, the data at the transmit side must be encoded with two or more different codes so that during decoding, each of the codes will modify the confidence of each bit accordingly. Each iteration of each code pushes the confidence of a given bit higher or lower, and consequently changes the hard decision value of the bits in error. Eventually, the data will settle on an arrangement where all codes are pushing the confidence of all bits higher.

5.3.7.2. TPC Encoding

The encoding of TPCs is straightforward with binary code blocks being generated in a single pass. The encoder starts with the first row of information bits and creates the follow-on bits to dictate parity. It does this for all rows of data bits. Next, the encoder does the same for each column, starting with the first and moving through the last. Once the parity actions on the data block are complete, the encoder performs parity calculations on the parity bits that were generated from the row functions. Figure 5.9 provides an example of a (8,4) x (8,4)

product code. While the example in Figure 5.9 shows an equal number of rows and columns, these need not be equal.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D | D | D | D | P | P | P | P |
| D | D | D | D | P | P | P | P |
| D | D | D | D | P | P | P | P |
| D | D | D | D | P | P | P | P |
| P | P | P | P | P | P | P | P |
| P | P | P | P | P | P | P | P |
| P | P | P | P | P | P | P | P |
| P | P | P | P | P | P | P | P |

Figure 5.9. Makeup of a (8,4) x (8,4) Product Code

It should be noted that while the (8,4) Extended Hamming Code in Figure 5.7 has a d_{min} value of 4, the (64,16) TPC of Figure 5.9 has a d_{min} value of 16, thereby rendering the error-detecting capability of the latter four times as powerful as the former.

5.3.7.3. TPC Decoding

Decoding TPCs is much more complicated as each block is decoded one at a time in an iterative fashion with rows being decoded first, columns next with the process repeated until a set number of iterations is met or until a threshold in confidence is reached.

Each row is decoded using soft decision correlation decoding. The output is combined with original data and input into a decoder for each column using soft decision correlation decoding. The output of the column decoding is then input back into the row decoding. This continues until decoder settles on a valid transmitted code array or until the maximum number of iterations is reached. Each decoding iteration builds on the previous decoding performance.

Due to the power of Turbo Product Coding teamed with its market acceptance, it was chosen as the forward error correction method to be utilized for this study.

6. Network Wide Tradeoffs

When selecting the proper network configuration and parameters, it is necessary to consider a number of elements. Only through the proper investigation and trading off of the advantages and disadvantages of each of these can the proper solution be chosen.

6.1. Shared vs. Individual

As discussed in Section 4, the main advantage of a shared carrier lies in the ability of remote sites to borrow bandwidth from other sites when it is not needed. However, in addition to the decreased IP Rate to Information Rate efficiency ratios of a shared carrier versus a dedicated carrier, another disadvantage lies in the role of the worst-case site within the network. When a shared carrier is used to support multiple remotes, as in the case of TDM, TDMA and MCPC, the modulation and coding that meets the requirements of all sites, including the worst-case site, must be chosen to meet a given SLA across the entire network.

Unfortunately, the worst-case site therefore disadvantages all of the other sites on the network and does not allow the network to be sized in the most efficient manner possible, in terms of pure Mbps per MHz.

6.2. Worst-Case Site Mod/Cod Selection

For example, a carrier being shared by five geographically dispersed sites, each falling within different EIRP and G/T contours and rain regions (more of a factor with Ku-Band than C-Band), would be designed using the modulation and coding rate of the worst-case site. Table 6.1 provides a breakdown of the modulation and coding for each site that most closely equates allocated bandwidth and PEB. Also shown is the resulting spectral efficiency, in terms of Mbps / MHz.

| Site Number | Modulation | Coding | Spectral Efficiency |
|-------------|------------|--------|---------------------|
| 1 | 8PSK | 3/4 | 2.25 |
| 2 | 8PSK | 7/8 | 2.625 |
| 3 | QPSK | 3/4 | 1.50 |
| 4 | QPSK | 7/8 | 1.75 |
| 5 | 8PSK | 7/8 | 2.625 |

Table 6.1 Per-Site Best-Case Modulation and Coding with Resulting Spectral Efficiency

From this example, it can be seen that the links for two of the five sites, if operating individually, would be able to utilize a modulation and coding combination that would result in a 2.625 Mbps / MHz ratio. In addition, one of the sites would operate with a 2.25 Mbps / MHz

ratio while another would operate at 1.75 Mbps / MHz. In this case, however, there is one site that would require a less aggressive modulation and coding method (QPSK ¾) that would result in only a 1.50 Mbps / MHz ratio. Because of this, a shared carrier that would support all five of these sites simultaneously would have to utilize a modulation / coding pair of QPSK ¾, which would result in a 1.50 Mbps / MHz ratio.

6.3. HPA Size

For a given antenna size, the required HPA power to transmit a carrier is proportional to the transmitted information rate. In other words, the higher the information rate, the larger the HPA that is required. In the case of a shared network, carrier sizes are typically larger than any one remote’s highest demanding data rate. Table 6.2 provides a summary of the total HPA power required for the Maximum Burst Rate for each site along with the HPA power required for the larger shared carrier.

| Site Number | Maximum Burst Rate | HPA Size for Maximum Burst Rate | Carrier Rate | HPA Size for Carrier |
|-------------|--------------------|---------------------------------|--------------|----------------------|
| 1 | 512 kbps | 5 Watts | 1024 kbps | 10 Watts |
| 2 | 512 kbps | 5 Watts | 1024 kbps | 10 Watts |

| | | | | |
|----------|----------|---------|-----------|----------|
| 3 | 512 kbps | 5 Watts | 1024 kbps | 10 Watts |
| 4 | 512 kbps | 5 Watts | 1024 kbps | 10 Watts |
| 5 | 512 kbps | 5 Watts | 1024 kbps | 10 Watts |

Table 6.2 Per-Site HPA Size Requirements

It can be seen that while each site would require only 5 Watts if it was to transmit at its maximum information rate. In the case of a shared carrier, each site must transmit in a time division multiple access fashion at the larger carrier rate to ensure proper demodulation and decoding at the downlink site. In this example, because each site must transmit at 1024 kbps, additional HPA power is required, which significantly increases the cost of each remote site due to the increased hardware performance requirement.

6.4. Antenna Size

Likewise, for a given HPA size, the required antenna size to transmit a carrier is proportional to the transmitted information rate. In other words, the higher the information rate, the larger the antenna that is required. Once again, in the case of a shared network, carrier sizes are typically larger than any one remote's highest demanding data rate. Table 6.3

provides a summary of the antenna size required for the Maximum Burst Rate for each site along with the antenna size required for the larger shared carrier.

| Site Number | Maximum Burst Rate | Antenna Size | Carrier Rate | Antenna Size |
|-------------|--------------------|--------------|--------------|--------------|
| 1 | 512 kbps | 1.8M | 1024 kbps | 2.4M |
| 2 | 512 kbps | 1.8M | 1024 kbps | 2.4M |
| 3 | 512 kbps | 1.8M | 1024 kbps | 2.4M |
| 4 | 512 kbps | 1.8M | 1024 kbps | 2.4M |
| 5 | 512 kbps | 1.8M | 1024 kbps | 2.4M |

Table 6.3 Per-Site Antenna Size Requirements

It can be seen that while each site would require a 1.8M if it was to transmit at its maximum information rate. In the case of a shared carrier, each site must transmit in a time division fashion at the larger carrier rate to ensure proper demodulation and decoding at the downlink site. In this example, because each site must transmit at 1024 kbps, a larger antenna is required, which increases the cost of each remote site due to the increased hardware performance requirement.

7. Description of Tools

There are two tools used for this study, one with an IP focus and one with an RF focus. The first is an Excel-based IP sizing tool that takes into account data traffic characteristics to provide an overall Information Rate required per satellite channel. The second tool, The Lease Transmission Plan Program, Version 5 (v 1.7.2), Communications Systems Engineering, Data Source IESS 410 Rev. 8b, May 2001, also called LST-5, is the Intelsat link budget tool used to perform link budget calculations on the Intelsat global fleet of satellites. To gather the results of this study, the Excel-based IP sizing tool was used first to generate the total amount of data to be sent over the communications channel. This total user bandwidth (in Mbps) was then entered into the LST-5 tool to generate a number of different design options, with varying number of carriers and modulation / coding combinations, to analyze the different tradeoffs in terms of total bandwidth and required remote hardware, in terms of power, that would be required. The analysis teams different permutations of n-ary modulation techniques (QPSK, 8PSK) with different FEC techniques (0.66, 0.75, 0.793, 0.875) to provide the reader an understanding of the advantages and disadvantages of using two different point-to-multipoint methods:

- TDM outbound with TDMA inbounds
- TDM outbound with SCPC inbounds

7.1. Excel IP Sizing Tool

An Excel sizing tool was created for this study to allow a given traffic mix (total IP Rate to be supported) to be translated into required carrier sizes (Information Rate to be transmitted). This section describes all of the parameters used and the calculations performed within this tool.

7.1.1. Network Parameter Inputs

Number of Sites (Number_Sites):

This is the number of sites per network. For this study, the number of sites was held constant at 20.

Number_Sites = 20

7.1.2. Outbound Link Parameters

The following describes the encapsulation method used on the outbound link of both solutions.

7.1.2.1. Inputs:

Outbound Committed Information Rate (CIR) (Out_CIR):

This input is the CIR per site. This CIR is always available to a remote independent upon whether the remote has information to transmit over the satellite link. For this study, this variable ranged from 128 to 384 kbps in 128 kbps increments.

Out_CIR = 128, 256 or 384 kbps

Outbound Maximum Burstable Rate (MBR) (Out_MBR):

This input is the MBR per site. This MBR is available on a best-effort basis and is the maximum rate to which a particular remote can burst to, resources permitting. For this study, this variable was held at constant at 512 kbps.

Out_MBR = 512 kbps

Oversubscription Ratio (Out_Oversub):

This input is the desired oversubscription ratio per site. Oversubscription focuses on the number of remotes that share the best-effort satellite resource. While the remote will always have its CIR assigned to it, the difference between the MBR and CIR is made available on a best-effort basis and this ratio determines what the chances are that bandwidth will be available above the CIR. For example, an Oversubscription ratio of 5 signifies that an amount of bandwidth (MBR-CIR) is assigned to 5 remotes simultaneously. In general, the higher the oversubscription ratio, the lower the probability that the excess bandwidth will be available for

the remote. Conversely, the lower the oversubscription ratio, the more likely bandwidth will be available. For this study, this variable ranged from 2 to 10 in increments of 2.

Out_Oversub = 2, 4, 6, 8 or 10

Average Maximum Transmission Unit (MTU) (Avg_MTU):

This input is the average the MTU of all Ethernet frames on the wire. For this study, it is assumed that all packets within this network have an MTU size of 1500 bytes.

Avg_MTU = 1500 Bytes

7.1.2.2. Calculated Values:

Average Frame Size (Avg_Frame):

This calculation shows the average frame size of Ethernet frames on the wire. If a compression algorithm was to be performed on the payload of the Ethernet frame, this field would be lower than the Average MTU input. This study does not consider the implementation of a compression and therefore the Average Frame Size will always equal the Average MTU size:

Avg_Frame = Avg_MTU Bytes

Average kbps into modem per site (Out_Avg_kbps):

This calculation shows the average IP Rate into the modem per site, in kbps.

$$\text{Out_Avg_kbps} = \text{Out_CIR} + (\text{Out_MBR} - \text{Out_CIR}) / \text{Out_Oversub kbps}$$

Satellite High-Level Data Link Control (HDLC) overhead (Sat_HDLC_OH):

This is the number of bytes used to address packets destined for a remote over the satellite channel. For this study, this value is set to a constant of 8 bytes as this is sufficient to address and properly control packet flow.

$$\text{Sat_HDLC_OH} = 8 \text{ Bytes}$$

Ethernet header size (Eth_Head):

This is the size of the Ethernet header sent over the satellite link. The standard Ethernet header size is 14 bytes (made up of a 6 byte source address, a 6 byte destination address and a 2 byte length/type field). Because the satellite modem translates the source and destination addresses into HDLC addresses and properly routes traffic within the closed satellite network, this information need not be transmitted over the satellite link. While this information is not needed within the closed network, it is required at the remote end. Because of this, the remote modem appends the proper Ethernet header before forwarding it the outside network. Because of this, this value is set to a constant of 0 bytes.

$$\text{Eth_Head} = 0 \text{ Bytes}$$

Max Packets per Second (PPS) per remote (Out_Max_PPS_Rem):

This calculation shows the maximum number of packets per second sent into the modem at the remote site.

$$\text{Out_Max_PPS_Rem} = (\text{Out_MBR} * 1000) / ((\text{Avg_Frame} + \text{Eth_Head}) * 8) \text{ PPS}$$

This value is rounded up to the next integer value.

Average PPS per remote (Out_Avg_PPS_Rem):

This calculation shows the average number of packets per second sent into the modem at the remote site.

$$\text{Out_Avg_PPS_Rem} = (\text{Out_Avg_kbps} * 1000) / ((\text{Avg_Frame} + \text{Eth_Head}) * 8) \text{ PPS}$$

This value is rounded up to the next integer value.

Max overhead (Out_Max_OH):

This calculation shows the maximum amount of overhead required for transmission over the satellite link per site.

$$\text{Out_Max_OH} = (\text{Out_Max_PPS_Rem} * \text{Sat_HDLC_OH}) * 8 / 1000 \text{ kbps}$$

Average overhead (Out_Avg_OH):

This calculation shows the average amount of overhead sent per site.

$$\text{Out_Avg_OH} = (\text{Out_Avg_PPS_Rem} * \text{Sat_HDLC_OH}) * 8 / 1000 \text{ kbps}$$

Max Info Rate per remote (Out_Max_Info_Rate_Rem):

This calculation shows the maximum Information Rate per remote.

$$\text{Out_Max_Info_Rate_Rem} = (\text{Avg_Frame} * 8 * \text{Out_Max_PPS_Rem}) / 1000 +$$

Out_Max_OH kbps

Average Info Rate per remote (Out_Avg_Info_Rate_Rem):

This calculation shows the average Information Rate per remote.

$$\text{Out_Avg_Info_Rate_Rem} = (\text{Avg_Frame} * 8 * \text{Out_Avg_PPS_Rem}) / 1000 + \text{Out_Avg_OH}$$

Total Outbound Info Rate within network (Total_Out_Info):

This calculation is the total outbound Information Rate within the network and is the resulting size of the outbound TDM carrier.

$$\text{Total_Out_Info} = \text{Out_Avg_Info_Rate_Rem} * \text{Number_Sites} \text{ kbps}$$

7.1.3. Inbound Link Parameters

The following describes the encapsulation method used on the inbound link of both solutions.

7.1.3.1. Inputs:

Inbound CIR (In_CIR):

This input is the CIR per site. This CIR is always available to a remote independent upon whether the remote has information to transmit over the satellite link. For this study, this variable ranged from 128 kbps to 384 kbps in 128 kbps increments.

In_CIR = 128, 256 or 384 kbps

Inbound MBR (In_MBR):

This input is the MBR per site. This MBR is available on a best-effort basis and is the maximum rate to which a particular remote can burst to, resources permitting. For this study, this variable was held at constant at 512 kbps.

In_MBR = 512 kbps

Oversubscription Ratio (In_Oversub):

This input is the desired oversubscription ratio per site. Oversubscription focuses on the number of remotes that share the best-effort satellite resource. While the remote will always have its CIR assigned to it, the difference between the MBR and CIR is made available on a best-effort basis and this ratio determines what the chances are that bandwidth will be available above the CIR. . For example, an Oversubscription ratio of 5 signifies that an amount of bandwidth (MBR-CIR) is assigned to 5 remotes simultaneously. In general, the higher the oversubscription ratio, the less probability that the excess bandwidth will be available for the remote. Conversely, the lower the oversubscription ratio, the more likely bandwidth will be available. For this study, this variable ranged from 2 to 10 in increments of 2.

In_Oversub = 2, 4, 6, 8 or 10

Average MTU (Avg_MTU):

This input is the average of the MTU of all Ethernet frames on the wire. For this study, it is assumed that all packets within this network have an MTU size of 1500 bytes.

Avg_MTU = 1500 Bytes

7.1.3.2. Calculated Values:

Average Frame Size (Avg_Frame):

This calculation shows the average frame size of Ethernet frames on the wire. If a compression algorithm was to be performed on the payload of the Ethernet frame, this field

would be lower than the Average MTU input. This study does not consider the implementation of a compression and therefore the Average Frame Size will always equal the Average MTU size.

$$\text{Avg_Frame} = \text{Avg_MTU Bytes}$$

Average kbps into modem per site (In_Avg_kbps):

This calculation shows the average IP Rate into the modem per site, in kbps.

$$\text{In_Avg_kbps} = \text{In_CIR} + (\text{In_MBR} - \text{In_CIR}) / \text{In_Oversub kbps}$$

Satellite HDLC overhead (Sat_HDLC_OH):

This is the number of bytes used to address packets destined for a remote over the satellite channel. For this study, this value is set to a constant of 8 bytes as this is sufficient to address and properly control packet flow.

$$\text{Sat_HDLC_OH} = 8 \text{ Bytes}$$

Ethernet header size (Eth_Head):

This is the size of the Ethernet header sent over the satellite link. The standard Ethernet header size is 14 bytes (made up of a 6 byte source address, a 6 byte destination address and a 2 byte length/type field). Because the satellite modem translates the source and destination addresses into HDLC addresses and properly routes traffic within the closed satellite network,

this information need not be transmitted over the satellite link. While this information is not needed within the closed network, it is required at the remote end. Because of this, the remote modem appends the proper Ethernet header before forwarding it the inside network. Because of this, this value is set to a constant of 0 bytes.

Eth_Head = 0 Bytes

Max PPS per remote (In_Max_PPS_Rem):

This calculation shows the maximum number of packets per second sent into the modem at the remote site.

$$\text{In_Max_PPS_Rem} = (\text{In_MBR} * 1000) / ((\text{Avg_Frame} + \text{Eth_Head}) * 8) \text{ PPS}$$

This value is rounded up to the next integer value.

Average PPS per remote (In_Avg_PPS_Rem):

This calculation shows the average number of packets per second sent into the modem at the remote site.

$$\text{In_Avg_PPS_Rem} = (\text{In_Avg_kbps} * 1000) / ((\text{Avg_Frame} + \text{Eth_Head}) * 8)$$

PPS

This value is rounded up to the next integer value.

Max PPS in Network (In_Max_PPS_Network):

This calculation shows the maximum number of packets per second that traverses the satellite link in the inbound direction.

$$\text{In_Max_PPS_Network} = \text{In_Max_PPS_Rem} * \text{Number_Sites}$$

This value is rounded up to the next integer value.

Average PPS in Network (In_Avg_PPS_Network):

This calculation shows the average number of packets per second that traverses the satellite link in the inbound direction.

$$\text{In_Avg_PPS_Network} = \text{In_Avg_PPS_Rem} * \text{Number_Sites}$$

This value is rounded up to the next integer value.

Max overhead (In_Max_OH):

This calculation shows the maximum amount of overhead required for transmission over the satellite link per site.

$$\text{In_Max_OH} = (\text{In_Max_PPS_Rem} * \text{Sat_HDLC_OH}) * 8 / 1000 \text{ kbps}$$

Average overhead (In_Avg_OH):

This calculation shows the average amount of overhead sent per site.

$$\text{In_Avg_OH} = (\text{In_Avg_PPS_Rem} * \text{Sat_HDLC_OH}) * 8 / 1000 \text{ kbps}$$

Max SCPC Inbound Info Rate per remote (SCPC_In_Max_Info_Rate_Rem):

This calculation shows the maximum Information Rate per remote for the SCPC inbound link.

$$\text{SCPC_In_Max_Info_Rate_Rem} = (\text{Avg_Frame} * 8 * \text{In_Max_PPS_Rem}) / 1000 + \text{In_Max_OH} \text{ kbps}$$

7.1.4. TDMA Only

7.1.4.1. Inputs

IP Rate / Information Rate for .66 FEC (IP_Info_660)

This input states the efficiency ratio of the TDMA inbound channel that utilizes a 0.66 Turbo Product Code FEC mechanism. For this study, to best emulate a real-world scenario, this parameter was set to:

$$\text{IP_Info_660} = 77.4\%$$

IP Rate / Information Rate for .793 FEC (IP_Info_793)

This input states the efficiency ratio of the TDMA inbound channel that utilizes a 0.793 Turbo Product Code FEC mechanism. For this study, to best emulate a real-world scenario, this parameter was set to:

$$\text{IP_Info_793} = 91.0\%$$

7.1.4.2. Calculations

Average TDMA Inbound IP Rate per remote (TDMA_In_Avg_Info_Rate_Rem)

This calculation shows the average IP Rate per remote.

$$\text{TDMA_In_Avg_Info_Rate_Rem} = (\text{Avg_Frame} * 8 * \text{In_Avg_PPS_Rem}) / 1000 + \text{In_Avg_OH}$$

This is an important value as it states the total resource required, per remote, in the inbound direction, on average, over time. This value is used to determine the total aggregate IP rate required to support the entire network.

Size of TDMA Carrier for .66 FEC with 20 Remotes (TDMA_Size_660_2)

$$\text{TDMA_Size_660_2} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_660}) * 2$$

Size of TDMA Carrier for .793 FEC with 20 Remotes (TDMA_Size_793_2)

$$\text{TDMA_Size_793_2} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_793}) * 2$$

Size of TDMA Carrier for .66 FEC with 4 Remotes (TDMA_Size_660_4)

$$\text{TDMA_Size_660_4} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_660}) * 4$$

Size of TDMA Carrier for .793 FEC with 4 Remotes (TDMA_Size_793_4)

$$\text{TDMA_Size_793_4} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_793}) * 4$$

Size of TDMA Carrier for .66 FEC with 5 Remotes (TDMA_Size_660_5)

$$\text{TDMA_Size_660_5} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_660}) * 5$$

Size of TDMA Carrier for .793 FEC with 5 Remotes (TDMA_Size_793_5)

$$\text{TDMA_Size_793_5} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_793}) * 5$$

Size of TDMA Carrier for .66 FEC with 10 Remotes (TDMA_Size_660_10)

$$\text{TDMA_Size_660_10} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_660}) * 10$$

Size of TDMA Carrier for .793 FEC with 10 Remotes (TDMA_Size_793_10)

$$\text{TDMA_Size_793_10} = (\text{TDMA_In_Avg_Info_Rate_Rem} / \text{IP_Info_793}) * 10$$

7.2. LST-5 Link Budget Tool

The exact determination of the total amount of transponder power resource required for a link (and therefore the ideal modulation and FEC combination to be utilized for a link) is a very complicated and time consuming endeavor. Luckily, there are several link budget tools in existence, including SatMaster Pro and LST-5.

The LST-5 program is Intelsat's customer tool that is updated periodically with updated Intelsat spacecraft information. Because of the fact that an Intelsat satellite was chosen for this study, the LST-5 tool was leveraged for this study. It is a user-friendly tool that makes heavy use of input forms, which allows for easy input validation, allowing the user to call up help as necessary for assistance with range, type and definition of input parameters. This validation helps the user minimize the probability that bad input data is entered.

8. Description of Network Characteristics

8.1. Number of Sites

While VSAT networks range in size from 10 to 10,000 (or more), for this study, it was assumed that the star topology satellite network consisted of a single hub and 20 remotes. This is typical in practice for the traffic characteristics chosen for this study.

8.2. Satellite

For this study, it was assumed that the IS-907 satellite was to be used. In particular, the Hemi C-Band beam of IS-907 was chosen. All link budget calculations using LST-5 assumed the satellite parameters of this beam. Figure 8.1 provides a summary of this satellite's characteristics.



| Spacecraft Parameters | | Total Transponder Beam Edge Parameters | |
|---|---|---|--------------------------|
| Lease Name | LST-plan | Intelsat IS-907 | 21/21 |
| SVO-L Number | 1 | Bandwidth | 72.0 MHz |
| Satellite Flight | 907 | Polarization | Circular/Circular |
| Satellite Location (Deg. E) | 332.50 | Center Freq. (Up/Down) | 5.9700 / 3.7450 GHz |
| (Deg. W) | 27.50 | G/T | -6.6 dB/K |
| Operating Mode | Normal | U/L Meas. Improve. Factor: | .0 dB |
| Uplink Beam | EH | EIRP | 37.4 dBW |
| Downlink Beam | EH | D/L Meas. Improve. Factor: | .9 dB |
| Transponder Freq. Slot | 1-2 | Oper. Mode: | MultiCarrier Txpdr Lease |
| Amplifier Power Level | Normal | IBO | -5.4 dB |
| Amplifier Power (watts) | 61.8 | OBO | -4.5 dB |
| VSAT Optimized Transponder | <input type="checkbox"/> | Available Beam Edge Lease Resource | |
| SFD Beam Edge (dBW/m2) | <input type="checkbox"/> OMA -83.0 | Bandwidth | MHz |
| Lease BW (MHz) | <input checked="" type="radio"/> LST Calculated <input type="radio"/> User Specified | Operating FD | dBW/m2 |
|  | | EIRP | dBW |
| <input type="button" value="Accept"/> | | Number of Active Carriers: | 0 |
|  | | No Link Budget Analysis performed | |

Figure 8.1. IS-907 East Hemi Beam Characteristics

8.3. Hub and Remote Antennas

As mentioned in Section 3, one has to weigh the technical and economic advantages of the benefits of utilizing different size antennas. For this study, it was assumed that the hub antenna was 9.0 meters in diameter and all remote sites utilized a 2.4 meter antenna as these are typical sizes used in actual commercial practice. Figures 8.1 and 8.2 capture the

characteristics of these two antennas, including their locations, which reside within the country of Nigeria.



| Primary Input | | | |
|---|------------------------------------|---|---|
| <input checked="" type="checkbox"/> ES Code | 90 | <input type="checkbox"/> ES Name | |
| <input checked="" type="checkbox"/> Band | C-Band | <input type="checkbox"/> City (nearest) | |
| <input checked="" type="checkbox"/> Diameter | 9.0 meters | <input type="checkbox"/> Country | |
| <input type="checkbox"/> Intelsat Standard | | <input type="checkbox"/> Nominal Pat Adv (Tr) | 1.6 dB |
| <input checked="" type="checkbox"/> G/T* | Calculate 31.6 dB/K | <input type="checkbox"/> Nominal Pat Adv (Rx) | 2.1 dB |
| *G/T at 4 GHz or 11 GHz | | | |
| <input checked="" type="checkbox"/> Longitude | 7.6479 Deg. E | <input type="checkbox"/> 7 Deg | 38 Min 52 Sec |
| <input checked="" type="checkbox"/> Latitude | 6.9231 Deg. N | <input type="checkbox"/> 6 Deg | 55 Min 23 Sec |
| Other Input | | | |
| <input checked="" type="checkbox"/> Tracking | None | <input type="checkbox"/> LNA Temperature | 33.0 K |
| <input type="checkbox"/> Elevation Angle | 48.5 Deg | <input type="checkbox"/> Feed Losses | .2 dB |
| <input type="checkbox"/> Azimuth Angle | 260.3 Deg | <input type="checkbox"/> VSWR LNA | 1.2 |
| <input type="checkbox"/> Polarization Sense | Circular | <input type="checkbox"/> Sidelobe Constant | 32.0 dBi |
| <input type="checkbox"/> Ant. Efficiency (Tr) | .70 | <input type="checkbox"/> Peak Ant. Gain (Tr) | 53.5 dBi |
| <input type="checkbox"/> Ant. Efficiency (Rx) | .70 | <input type="checkbox"/> Peak Ant. Gain (Rx) | 49.4 dBi |
| <input type="checkbox"/> ESIS Database | | <input checked="" type="checkbox"/> - User Specified | <input type="checkbox"/> - LST Calculated |
| Frequencies Assumed: 5.9700 / 3.7450 | |   | |
| Current Satellite Location: 332.50 °E | | | |
| Return | Accept and Save to LST plan | Copy ES | Cancel |
| Write into Local ES DB | | | |

Figure 8.2. Hub Antenna Characteristics

| Primary Input | | | |
|---|------------------------------------|--|---|
| <input checked="" type="checkbox"/> ES Code | 24 | <input type="checkbox"/> ES Name | |
| <input checked="" type="checkbox"/> Band | C-Band | <input type="checkbox"/> City (nearest) | |
| <input checked="" type="checkbox"/> Diameter | 2.4 meters | <input type="checkbox"/> Country | |
| <input checked="" type="checkbox"/> Intelsat Standard | | <input type="checkbox"/> Nominal Pat Adv (Tr) | 1.7 dB |
| G/T* | Calculate 19.5 dB/K | <input type="checkbox"/> Nominal Pat Adv (Rx) | 2.0 dB |
| * G/T at 4 GHz or 11 GHz | | | |
| Longitude | 7.2929 Deg. E | 7 Deg | 17 Min 34 Sec |
| Latitude | 7.6331 Deg. N | 7 Deg | 37 Min 59 Sec |
| Other Input | | | |
| <input checked="" type="checkbox"/> Tracking | None | <input type="checkbox"/> LNA Temperature | 30.0 K |
| <input type="checkbox"/> Elevation Angle | 48.8 Deg | <input type="checkbox"/> Feed Losses | .2 dB |
| <input type="checkbox"/> Azimuth Angle | 259.2 Deg | <input type="checkbox"/> VSWR LNA | 2.0 |
| <input type="checkbox"/> Polarization Sense | Circular | <input type="checkbox"/> Sidelobe Constant | 32.0 dBi |
| <input type="checkbox"/> Ant. Efficiency (Tr) | .65 | <input type="checkbox"/> Peak Ant. Gain (Tr) | 41.7 dBi |
| <input type="checkbox"/> Ant. Efficiency (Rx) | .65 | <input type="checkbox"/> Peak Ant. Gain (Rx) | 37.6 dBi |
| <input type="checkbox"/> ESIS Database | | <input checked="" type="checkbox"/> - User Specified | <input type="checkbox"/> - LST Calculated |
| Frequencies Assumed: 5.9700 / 3.7450 | | | |
| Current Satellite Location: 332.50 °E | | | |
| Return | Accept and Save to LST plan | Copy ES | Cancel Write into Local ES DB |

Figure 8.3. Remote Antenna Characteristics

8.4. RF Performance of Modem

It was the purpose of this study to follow a real-life scenario as closely as possible and because of this fact, commonly used satellite modems, antenna sizes, outdoor equipment sizes and satellite were chosen. Actual RF performance characteristics vary depending upon the Turbo Product Code chipset and the actual block code chosen. For this study, commonly used FEC rate options were selected for the TDM/MF-SCPC and TDM/MF-TDMA networks. To most

closely mimic a real-life comparison, it was also assumed that equipment used within the TDM/MF-SCPC and TDM/MF-TDMA scenarios would exhibit different RF performance in terms of required receive E_b/N_0 at the remote site to meet a Bit Error Rate (BER) of $10e(-8)$. Table 8.1 shows the different FEC rate options for TDMA and SCPC and also the required E_b/N_0 per option and E_b/N_0 required for a Bit Error Rate (BER) of $10e(-8)$:

| Method | Modulation | FEC Rate | E_b/N_0 (dB) | Block Size (bits) |
|---------------|-------------------|-----------------|----------------------------------|--------------------------|
| TDMA | QPSK | 0.66 | 4.9 | 1024 |
| TDMA | QPSK | 0.793 | 4.6 | 4096 |
| TDMA | 8PSK | 0.66 | 7.7 | 1024 |
| TDMA | 8PSK | 0.793 | 7.0 | 4096 |
| SCPC | QPSK | 0.75 | 4.5 | 4096 |
| SCPC | QPSK | 0.875 | 4.6 | 16384 |
| SCPC | 8PSK | 0.75 | 7.0 | 4096 |
| SCPC | 8PSK | 0.875 | 7.2 | 16384 |

Table 8.1. Block size and E_b/N_0

The TDMA modem under study uses a (64,57) x (64,57) two dimensional TPC code to create the 0.793 FEC and a (32,26) x (32,26) two dimensional TPC code to create the 0.660 FEC. Both of these are based upon the AHA 4540 chipset and use the native codes within.

The SCPC modem under study uses the same AHA chipset but takes the native codes and does code shortening and unique word insertion. For the 0.75 FEC, the (64,57) two dimensional code is used and for the 0.875 FEC, the (128,120) two dimensional code is used. This code shortening is done to get the proper 0.75 and 0.875 FEC codes.

The reason that the required E_b/N_0 for the 0.793 FEC is lower than the required E_b/N_0 for the 0.66 FEC is due to the fact that the 0.793 FEC uses a larger block and therefore has more error correcting capabilities within the TPC decoding process than the 0.66 FEC code, despite requiring only 20.7% redundancy bits versus 34% redundancy bits for the 0.66 FEC option.

The error correcting capabilities of a TPC implementation is a function of two variables:

- Block size
- Code rate

Codes with a small block sizes must have a lower code rate to achieve similar error correction performance. In general, the larger the block size, the better the performance and the lower the FEC rate, the stronger the performance.

These two codes were chosen because their coding gains are very close and due to the fact that within a TDMA network, it is essential to have a choice of block sizes. While 1kbit blocks are not as efficient from a data throughput standpoint, it is important to maximize the

number of slots within a TDMA frame to ensure that many remotes on a single TDMA channel can be fairly allocated bandwidth. The larger 4kbit block (0.793 FEC) option can be used for TDMA channels that do not support a high number of remotes.

Also, voice traffic is made up of very small IP packets. Because a slot cannot be shared between remotes, it is important to maximize the fill factor of slots and ensure that the proper slot size is chosen to support the traffic mix to minimize wasted slot space.

The 1kbit code performs worse than the 4kbit code at low BER ($10e(-8)$) due to the slightly different sloped roll off of the different block codes.

Due to the fact that the .793 FEC results in a 91.0% efficiency while the 0.66 FEC results in only a 77.4% efficiency, it would be logical to assume that the .793 FEC should be chosen in all cases. However a larger block size requires a more granular slot allocation to remotes since voice packets only need smaller slots. For this reason, any network that is to support voice or small IP packets, the 0.793 FEC should not be chosen. For this study, the 0.66 FEC option was selected for study.

9. Presentation of Results

This section presents all end result data for each of the 15 permutations of chosen CIR and Oversubscription Ratios, in terms of:

- Outbound Datarate (Mbps)
 - Same for all modulation and FEC selections for both TDM / MF-SCPC and TDM / MF-TDMA options
- Outbound HPA Requirement (Watts)
 - Differs per modulation and FEC selections for both TDM / MF-SCPC and TDM / MF-TDMA options
- Allocated Bandwidth Required for Outbound Carrier (MHz)
 - Differs per modulation and FEC selections for both TDM / MF-SCPC and TDM / MF-TDMA options
- Power Equivalent Bandwidth (PEB) Required for Outbound Carrier (MHz)
 - Differs per modulation and FEC selections for both TDM / MF-SCPC and TDM / MF-TDMA options
- Total Bandwidth for Outbound Carrier (MHz)
 - Greater of Outbound Allocated Bandwidth and Outbound PEB
- Inbound TDM / MF-SCPC Datarates (Mbps)

- Same for all modulation and FEC selections
- Allocated Bandwidth Required per Inbound TDM / MF-SCPC Carrier (MHz)
 - Differs per modulation and FEC selections
- Power Equivalent Bandwidth (PEB) Required per Inbound TDM / MF-SCPC Carrier (MHz)
 - Differs per modulation and FEC selections
- Inbound TDM / MF-SCPC HPA Requirement (Watts)
 - Differs per modulation and FEC selections
- Total Bandwidth per TDM / MF-SCPC Inbound Carrier (MHz)
 - Greater of Inbound Allocated Bandwidth and Inbound PEB
- Total Bandwidth for TDM / MF-SCPC Inbound Carriers (MHz)
 - Number of Carriers times Total Bandwidth per Inbound Carrier
- Total Bandwidth for Entire Network for TDM / MF-SCPC Option (MHz)
 - Total Bandwidth for Outbound Carrier plus Total Bandwidth for Inbound Carriers
- Inbound TDM / MF-TDMA Datarates (Mbps)
 - Same for all modulation and FEC selections
- Allocated Bandwidth Required per Inbound TDM / MF-TDMA Carrier (MHz)

- Differs per modulation and FEC selections
- Power Equivalent Bandwidth (PEB) Required per Inbound TDM / MF-TDMA Carrier (MHz)
 - Differs per modulation and FEC selections
- Inbound TDM / MF-TDMA HPA Requirement (Watts)
 - Differs per modulation and FEC selections
- Total Bandwidth per TDM / MF-TDMA Inbound Carrier (MHz)
 - Greater of Inbound Allocated Bandwidth and Inbound PEB
- Total Bandwidth for TDM / MF-TDMA Inbound Carriers (MHz)
 - Number of Carriers times Total Bandwidth per Inbound Carrier
- Total Bandwidth for Entire Network for TDM / MF-TDMA Option (MHz)
 - Total Bandwidth for Outbound Carrier plus Total Bandwidth for Inbound Carriers

Also included for each of the fifteen (15) CIR / Oversubscription Ratio is a scatter plot that compares the four (4) TDM / MF-SCPC and eight (8) TDM / MF-TDMA options to show the difference in required power (in Watts) at each remote versus the total required bandwidth (in MHz) of the complete network.

9.1. Results for 128 kbps CIR, 10:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth | |
|-----------------|--|----------------|------------|-------|-----------|-------|-------------|----------|-------------------|-----------|--|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction MHz | Total MHz | |
| | | CIR: 128 kbps | | | | | | | | | |
| | | Oversub: 10 :1 | | | | | | | | | |
| OUTBOUND | | 3.378 | | | | | | | | | |
| | | | 8PSK | 0.875 | 1.80 | 13.74 | 23.8 | 1 | 13.74 | | |
| | | | 8PSK | 0.75 | 2.10 | 9.88 | 17.1 | 1 | 9.88 | | |
| | | | QPSK | 0.875 | 2.70 | 3.52 | 6.1 | 1 | 3.52 | | |
| | | | QPSK | 0.750 | 3.15 | 3.28 | 5.7 | 1 | 3.28 | | |
| INBOUND | | 0.519 | | | | | | | | | |
| | | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 8.81 | |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 9.74 | |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 11.58 | |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 12.97 | |
| INBOUND | | 0.672 | | | | | | | | | |
| | | | 8PSK | 0.660 | 0.48 | 0.33 | 8.6 | 10 | 4.75 | 8.03 | |
| | | | QPSK | 0.660 | 0.71 | 0.15 | 4.0 | 10 | 7.13 | 10.41 | |
| | | 0.874 | | | | | | | | | |
| | | | 8PSK | 0.660 | 0.62 | 0.43 | 11.2 | 5 | 3.09 | 6.37 | |
| | | | QPSK | 0.660 | 0.93 | 0.20 | 5.2 | 5 | 4.64 | 7.91 | |
| | | 1.092 | | | | | | | | | |
| | | | 8PSK | 0.660 | 0.77 | 0.54 | 14.0 | 4 | 3.09 | 6.36 | |
| | | | QPSK | 0.660 | 1.16 | 0.25 | 6.5 | 4 | 4.63 | 7.91 | |
| | | 2.183 | | | | | | | | | |
| | | | 8PSK | 0.660 | 1.54 | 1.08 | 27.9 | 2 | 3.09 | 6.36 | |
| | | | QPSK | 0.660 | 2.32 | 0.49 | 13.0 | 2 | 4.63 | 7.91 | |

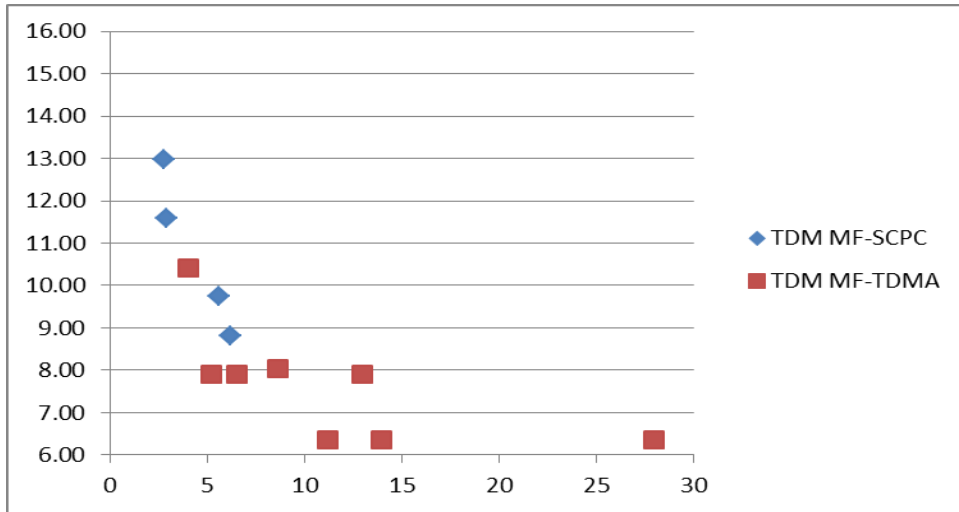


Figure 9.1: Results of 128 kbps CIR with 10:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.2. Results for 128 kbps CIR, 8:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth |
|----------------------|--------------|----------|------------|-------|-----------|-------|-------------|----------|---------------|-----------|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total |
| | | | | | | | | | MHz | MHz |
| CIR: 128 kbps | | | | | | | | | | |
| Oversub: 8 :1 | | | | | | | | | | |
| OUTBOUND | 3.619 | | 8PSK | 0.875 | 1.93 | 14.72 | 25.5 | 1 | 14.72 | |
| | | | 8PSK | 0.75 | 2.25 | 10.59 | 18.3 | 1 | 10.59 | |
| | | | QPSK | 0.875 | 2.89 | 3.77 | 6.5 | 1 | 3.77 | |
| | | | QPSK | 0.750 | 3.38 | 3.51 | 6.1 | 1 | 3.51 | |
| INBOUND | 0.519 | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 9.05 |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 9.97 |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 11.81 |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 13.20 |
| INBOUND | 0.672 | | 8PSK | 0.660 | 0.48 | 0.33 | 8.6 | 10 | 4.75 | 8.26 |
| | | | QPSK | 0.660 | 0.71 | 0.15 | 4.0 | 10 | 7.13 | 10.64 |
| | 0.936 | | 8PSK | 0.660 | 0.66 | 0.46 | 12.0 | 5 | 3.31 | 6.82 |
| | | | QPSK | 0.660 | 0.99 | 0.21 | 5.6 | 5 | 4.97 | 8.48 |
| | 1.170 | | 8PSK | 0.660 | 0.83 | 0.58 | 15.0 | 4 | 3.31 | 6.82 |
| | | | QPSK | 0.660 | 1.24 | 0.26 | 7.0 | 4 | 4.97 | 8.48 |
| | 2.339 | | 8PSK | 0.660 | 1.65 | 1.15 | 29.9 | 2 | 3.31 | 6.82 |
| | | | QPSK | 0.660 | 2.48 | 0.53 | 13.9 | 2 | 4.96 | 8.47 |

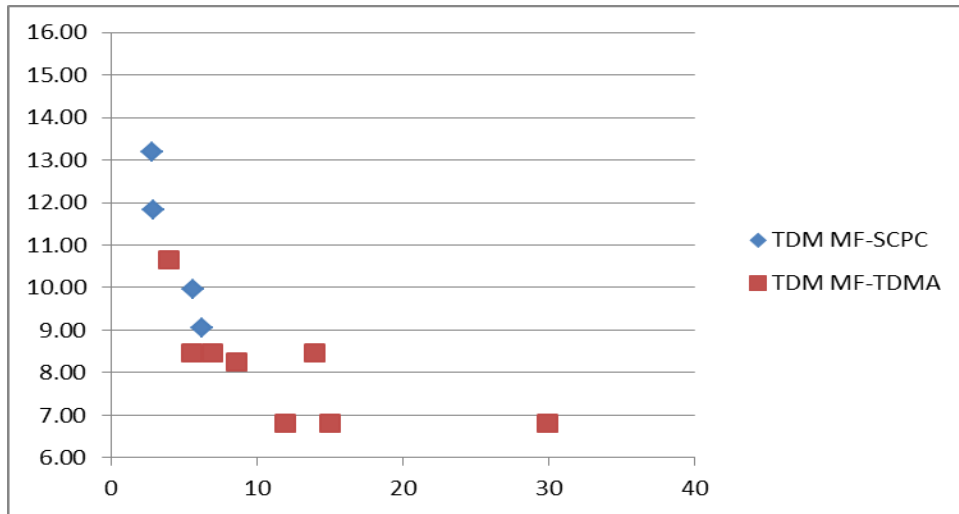


Figure 9.2: Results of 128 kbps CIR with 8:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.3. Results for 128 kbps CIR, 6:1 Oversubscription

| CIR: 128 kbps | | Oversub: 6 :1 | | | | | | | |
|-----------------|------------------|----------------------|-------------|------------------|------------|-----------------------|---------------|-----------------------------------|---------------------------|
| DIRECTION | Datarate Mbps | Modulation Q or 8 | FEC Rate | Allocated MHz | PEB MHz | ODU Power Watts | Carriers # | Bandwidth per Direction MHz | Bandwidth Total MHz |
| OUTBOUND | 3.86 | | | | | | | | |
| | | 8PSK | 0.875 | 2.06 | 15.70 | 27.2 | 1 | 15.70 | |
| | | 8PSK | 0.75 | 2.40 | 11.29 | 19.5 | 1 | 11.29 | |
| | | QPSK | 0.875 | 3.09 | 4.02 | 7.0 | 1 | 4.02 | |
| | | QPSK | 0.750 | 3.60 | 3.74 | 6.5 | 1 | 3.74 | |
| INBOUND | 0.519 | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 9.28 |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 10.20 |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 12.05 |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 13.43 |
| INBOUND | 0.672 | | | | | | | | |
| | | 8PSK | 0.660 | 0.48 | 0.33 | 8.6 | 10 | 4.75 | 8.49 |
| | | QPSK | 0.660 | 0.71 | 0.15 | 4.0 | 10 | 7.13 | 10.87 |
| | 0.998 | | | | | | | | |
| | | 8PSK | 0.660 | 0.71 | 0.49 | 12.8 | 5 | 3.53 | 7.27 |
| | | QPSK | 0.660 | 1.06 | 0.23 | 5.9 | 5 | 5.29 | 9.04 |
| | 1.247 | | | | | | | | |
| | | 8PSK | 0.660 | 0.88 | 0.61 | 16.0 | 4 | 3.53 | 7.27 |
| | | QPSK | 0.660 | 1.32 | 0.28 | 7.4 | 4 | 5.29 | 9.04 |
| | 2.494 | | | | | | | | |
| | | 8PSK | 0.660 | 1.76 | 1.23 | 31.9 | 2 | 3.53 | 7.27 |
| | | QPSK | 0.660 | 2.65 | 0.56 | 14.8 | 2 | 5.29 | 9.04 |

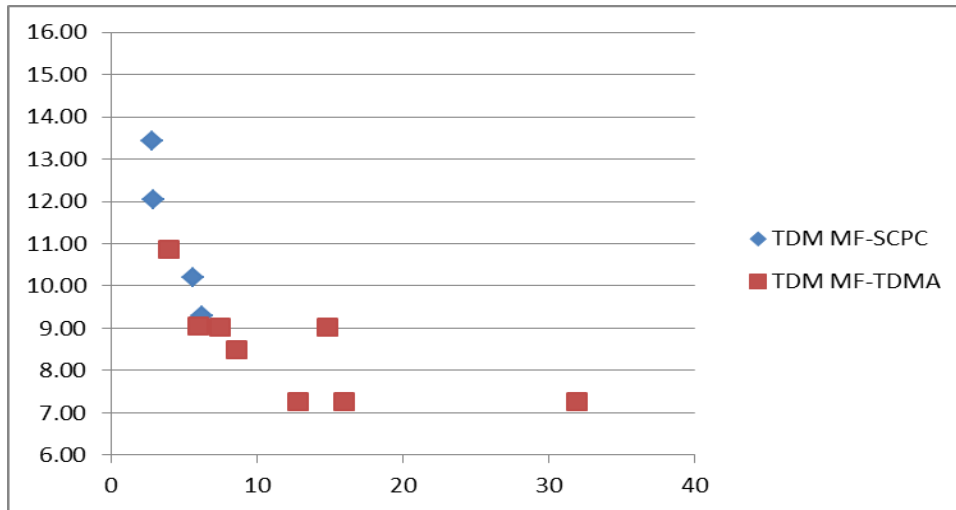


Figure 9.3: Results of 128 kbps CIR with 6:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.4. Results for 128 kbps CIR, 4:1 Oversubscription

| CIR: 128 kbps | | Oversub: 4:1 | | | | | | | |
|-----------------|------------------|----------------------|-------------|------------------|------------|-----------------------|---------------|-----------------------------------|---------------------------|
| DIRECTION | Datarate Mbps | Modulation Q or 8 | FEC Rate | Allocated MHz | PEB MHz | ODU Power Watts | Carriers # | Bandwidth per Direction MHz | Bandwidth Total MHz |
| OUTBOUND | 4.584 | | | | | | | | |
| | | 8PSK | 0.875 | 2.45 | 18.64 | 32.3 | 1 | 18.64 | |
| | | 8PSK | 0.75 | 2.85 | 13.41 | 23.2 | 1 | 13.41 | |
| | | QPSK | 0.875 | 3.67 | 4.78 | 8.3 | 1 | 4.78 | |
| | | QPSK | 0.750 | 4.28 | 4.45 | 7.7 | 1 | 4.45 | |
| INBOUND | 0.519 | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 9.98 |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 10.90 |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 12.75 |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 14.13 |
| INBOUND | 0.672 | | | | | | | | |
| | | 8PSK | 0.660 | 0.48 | 0.33 | 8.6 | 10 | 4.75 | 9.20 |
| | | QPSK | 0.660 | 0.71 | 0.15 | 4.0 | 10 | 7.13 | 11.58 |
| | 1.185 | | | | | | | | |
| | | 8PSK | 0.660 | 0.84 | 0.58 | 15.2 | 5 | 4.19 | 8.63 |
| | | QPSK | 0.660 | 1.26 | 0.27 | 7.1 | 5 | 6.29 | 10.73 |
| | 1.481 | | | | | | | | |
| | | 8PSK | 0.660 | 1.05 | 0.73 | 19.0 | 4 | 4.19 | 8.63 |
| | | QPSK | 0.660 | 1.57 | 0.33 | 8.8 | 4 | 6.29 | 10.73 |
| | 2.961 | | | | | | | | |
| | | 8PSK | 0.660 | 2.09 | 1.46 | 37.9 | 2 | 4.19 | 8.63 |
| | | QPSK | 0.660 | 3.14 | 0.67 | 17.6 | 2 | 6.28 | 10.73 |

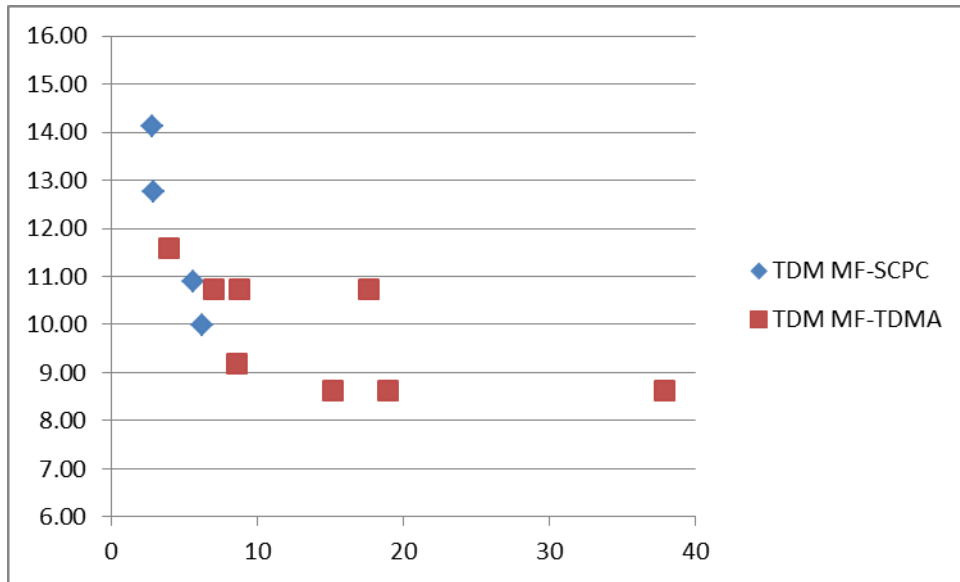


Figure 9.4: Results of 128 kbps CIR with 4:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.5. Results for 128 kbps CIR, 2:1 Oversubscription

| CIR: 128 kbps | | Oversub: 2 :1 | | | | | | | | |
|---------------|------------------|----------------------|-------------|------------------|------------|-----------------------|---------------|-----------------------------------|---------------------------|--|
| DIRECTION | Datarate Mbps | Modulation Q or 8 | FEC Rate | Allocated MHz | PEB MHz | ODU Power Watts | Carriers # | Bandwidth per Direction MHz | Bandwidth Total MHz | |
| OUTBOUND | 6.515 | | | | | | | | | |
| | | 8PSK | 0.875 | 3.48 | 26.49 | 45.9 | 1 | 26.49 | | |
| | | 8PSK | 0.75 | 4.05 | 19.06 | 33.0 | 1 | 19.06 | | |
| | | QPSK | 0.875 | 5.21 | 6.79 | 11.8 | 1 | 6.79 | | |
| | | QPSK | 0.750 | 6.08 | 6.32 | 11.0 | 1 | 6.32 | | |
| INBOUND | 0.519 | | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 11.86 | |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 12.78 | |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 14.62 | |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 16.01 | |
| INBOUND | 0.842 | | | | | | | | | |
| | | 8PSK | 0.660 | 0.60 | 0.41 | 10.8 | 10 | 5.95 | 12.27 | |
| | | QPSK | 0.660 | 0.89 | 0.19 | 5.0 | 10 | 8.93 | 15.25 | |
| | 1.683 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.19 | 0.83 | 21.6 | 5 | 5.95 | 12.27 | |
| | | QPSK | 0.660 | 1.78 | 0.38 | 10.0 | 5 | 8.92 | 15.24 | |
| | 2.104 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.49 | 1.03 | 27.0 | 4 | 5.95 | 12.27 | |
| | | QPSK | 0.660 | 2.23 | 0.47 | 12.5 | 4 | 8.93 | 15.25 | |
| | 4.208 | | | | | | | | | |
| | | 8PSK | 0.660 | 2.97 | 2.07 | 54.0 | 2 | 5.95 | 12.27 | |
| | | QPSK | 0.660 | 4.46 | 0.95 | 25.0 | 2 | 8.93 | 15.25 | |

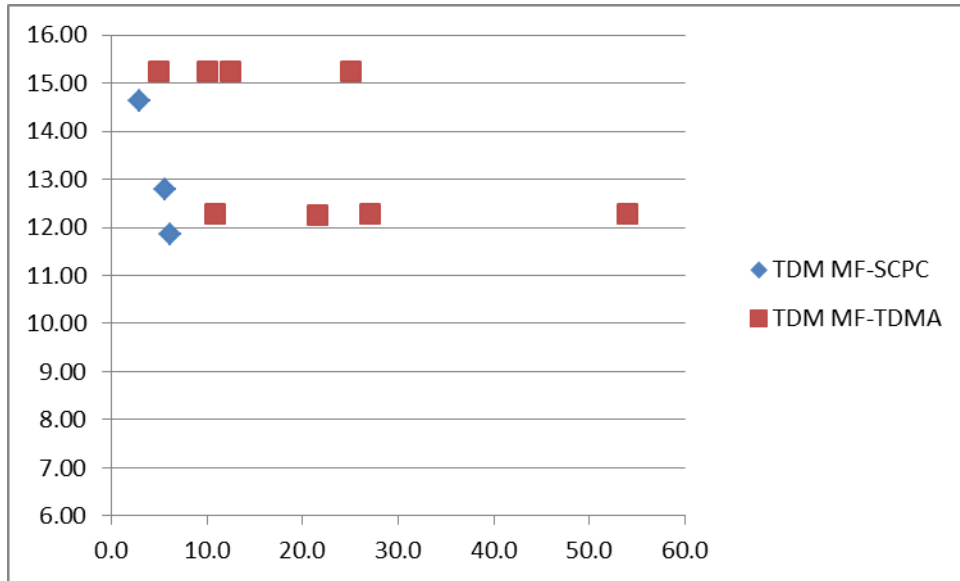


Figure 9.5: Results of 128 kbps CIR with 2:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.6. Results for 256 kbps CIR, 10:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth |
|-----------------------|--------------|----------|------------|-------|-----------|-------|-------------|----------|---------------|-----------|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total |
| | | | | | | | | | MHz | MHz |
| CIR: 256 kbps | | | | | | | | | | |
| Oversub: 10 :1 | | | | | | | | | | |
| OUTBOUND | 5.791 | | 8PSK | 0.875 | 3.09 | 23.55 | 40.8 | 1 | 23.55 | |
| | | | 8PSK | 0.75 | 3.60 | 16.94 | 29.3 | 1 | 16.94 | |
| | | | QPSK | 0.875 | 4.63 | 6.04 | 10.5 | 1 | 6.04 | |
| | | | QPSK | 0.750 | 5.41 | 5.62 | 9.8 | 1 | 5.62 | |
| INBOUND | 0.519 | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 11.15 |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 12.08 |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 13.92 |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 15.31 |
| INBOUND | 0.748 | | 8PSK | 0.660 | 0.53 | 0.37 | 9.6 | 10 | 5.29 | 10.91 |
| | | | QPSK | 0.660 | 0.79 | 0.17 | 4.4 | 10 | 7.93 | 13.55 |
| | 1.496 | | 8PSK | 0.660 | 1.06 | 0.74 | 19.2 | 5 | 5.29 | 10.91 |
| | | | QPSK | 0.660 | 1.59 | 0.34 | 8.8 | 5 | 7.93 | 13.55 |
| | 1.870 | | 8PSK | 0.660 | 1.32 | 0.93 | 24.0 | 4 | 5.29 | 10.91 |
| | | | QPSK | 0.660 | 1.98 | 0.42 | 11.0 | 4 | 7.93 | 13.55 |
| | 3.741 | | 8PSK | 0.660 | 2.65 | 1.85 | 48.0 | 2 | 5.29 | 10.91 |
| | | | QPSK | 0.660 | 3.97 | 0.85 | 22.0 | 2 | 7.93 | 13.55 |

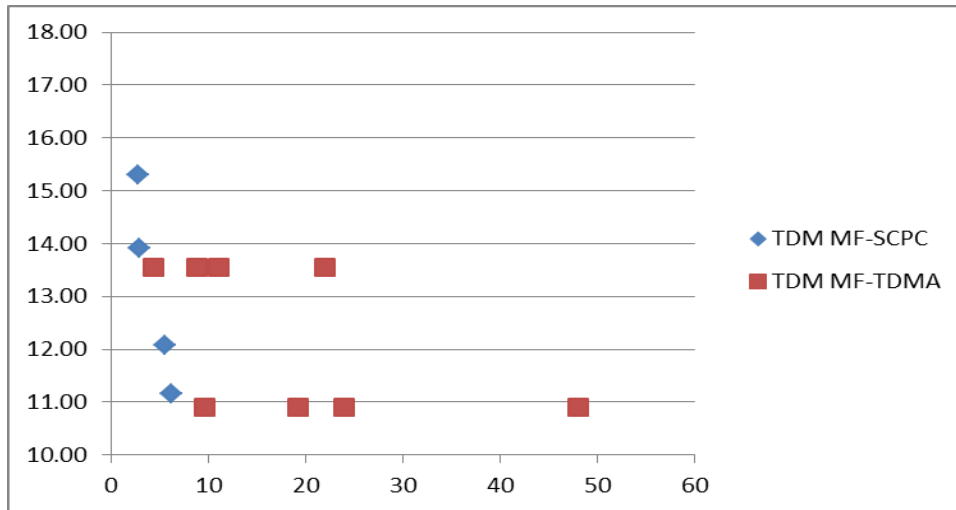


Figure 9.6: Results of 256 kbps CIR with 10:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.7. Results for 256 kbps CIR, 8:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth | |
|-----------------|--|---------------|------------|-------|-----------|-------|-------------|----------|---------------|-----------|--|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total | |
| | | | | | | | | | MHz | MHz | |
| | | CIR: 256 kbps | | | | | | | | | |
| | | Oversub: 8 :1 | | | | | | | | | |
| OUTBOUND | | 5.791 | | | | | | | | | |
| | | | 8PSK | 0.875 | 3.09 | 23.55 | 40.8 | 1 | 23.55 | | |
| | | | 8PSK | 0.75 | 3.60 | 16.94 | 29.3 | 1 | 16.94 | | |
| | | | QPSK | 0.875 | 4.63 | 6.04 | 10.5 | 1 | 6.04 | | |
| | | | QPSK | 0.750 | 5.41 | 5.62 | 9.8 | 1 | 5.62 | | |
| INBOUND | | 0.519 | | | | | | | | | |
| | | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 11.15 | |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 12.08 | |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 13.92 | |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 15.31 | |
| INBOUND | | 0.748 | | | | | | | | | |
| | | | 8PSK | 0.660 | 0.53 | 0.37 | 9.6 | 10 | 5.29 | 10.91 | |
| | | | QPSK | 0.660 | 0.79 | 0.17 | 4.4 | 10 | 7.93 | 13.55 | |
| | | 1.496 | | | | | | | | | |
| | | | 8PSK | 0.660 | 1.06 | 0.74 | 19.2 | 5 | 5.29 | 10.91 | |
| | | | QPSK | 0.660 | 1.59 | 0.34 | 8.8 | 5 | 7.93 | 13.55 | |
| | | 1.870 | | | | | | | | | |
| | | | 8PSK | 0.660 | 1.32 | 0.93 | 24.0 | 4 | 5.29 | 10.91 | |
| | | | QPSK | 0.660 | 1.98 | 0.42 | 11.0 | 4 | 7.93 | 13.55 | |
| | | 3.741 | | | | | | | | | |
| | | | 8PSK | 0.660 | 2.65 | 1.85 | 48.0 | 2 | 5.29 | 10.91 | |
| | | | QPSK | 0.660 | 3.97 | 0.85 | 22.0 | 2 | 7.93 | 13.55 | |

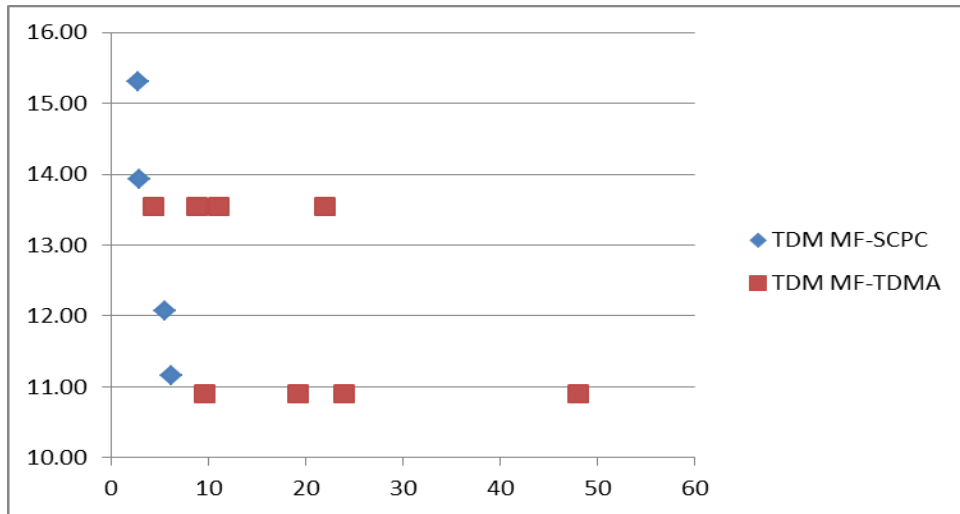


Figure 9.7: Results of 256 kbps CIR with 8:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.8. Results for 256 kbps CIR, 6:1 Oversubscription

| CIR: 256 kbps | | Oversub: 6 :1 | | | | | | | |
|-----------------|------------------|----------------------|-------------|------------------|------------|-----------------------|---------------|-----------------------------------|---------------------------|
| DIRECTION | Datarate Mbps | Modulation Q or 8 | FEC Rate | Allocated MHz | PEB MHz | ODU Power Watts | Carriers # | Bandwidth per Direction MHz | Bandwidth Total MHz |
| OUTBOUND | 6.032 | | | | | | | | |
| | | 8PSK | 0.875 | 3.22 | 24.53 | 42.5 | 1 | 24.53 | |
| | | 8PSK | 0.75 | 3.75 | 17.65 | 30.5 | 1 | 17.65 | |
| | | QPSK | 0.875 | 4.82 | 6.29 | 10.9 | 1 | 6.29 | |
| | | QPSK | 0.750 | 5.63 | 5.85 | 10.2 | 1 | 5.85 | |
| INBOUND | 0.519 | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 11.39 |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 12.31 |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 14.16 |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 15.54 |
| INBOUND | 0.779 | | | | | | | | |
| | | 8PSK | 0.660 | 0.55 | 0.38 | 10.0 | 10 | 5.51 | 11.36 |
| | | QPSK | 0.660 | 0.83 | 0.18 | 4.6 | 10 | 8.26 | 14.11 |
| | 1.559 | | | | | | | | |
| | | 8PSK | 0.660 | 1.10 | 0.77 | 20.0 | 5 | 5.51 | 11.37 |
| | | QPSK | 0.660 | 1.65 | 0.35 | 9.2 | 5 | 8.27 | 14.12 |
| | 1.948 | | | | | | | | |
| | | 8PSK | 0.660 | 1.38 | 0.96 | 25.0 | 4 | 5.51 | 11.36 |
| | | QPSK | 0.660 | 2.07 | 0.44 | 11.5 | 4 | 8.26 | 14.11 |
| | 3.897 | | | | | | | | |
| | | 8PSK | 0.660 | 2.76 | 1.92 | 50.0 | 2 | 5.51 | 11.36 |
| | | QPSK | 0.660 | 4.13 | 0.88 | 23.0 | 2 | 8.26 | 14.12 |

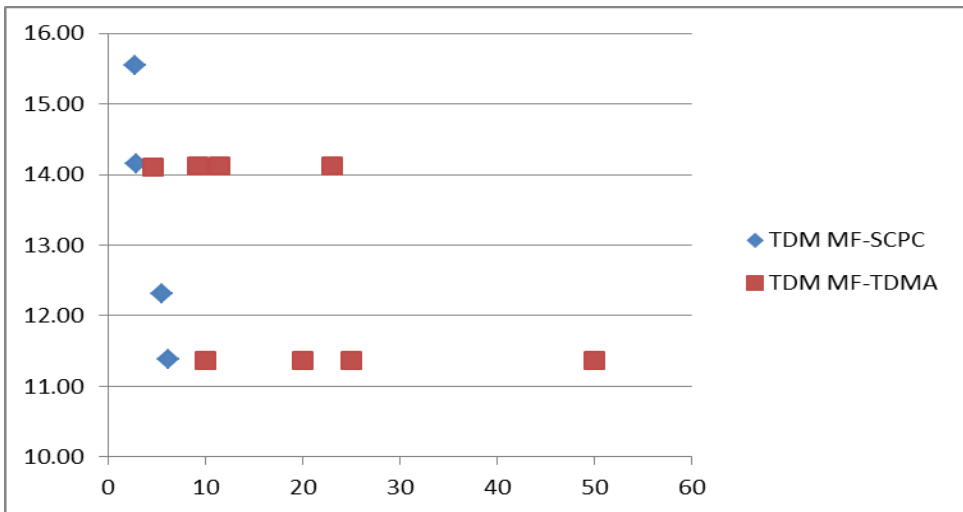


Figure 9.8: Results of 256 kbps CIR with 6:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.9. Results for 256 kbps CIR, 4:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth |
|-----------------|--|--------------|------------|-------|-----------|-------|-------------|----------|---------------|-----------|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total |
| | | | | | | | | | MHz | MHz |
| CIR: | | 256 | | | | | | | | |
| Oversub: | | 4 | | | | | | | | |
| | | | | | | | | | | |
| OUTBOUND | | 6.515 | | | | | | | | |
| | | | 8PSK | 0.875 | 3.48 | 26.49 | 45.9 | 1 | 26.49 | |
| | | | 8PSK | 0.75 | 4.05 | 19.06 | 33.0 | 1 | 19.06 | |
| | | | QPSK | 0.875 | 5.21 | 6.79 | 11.8 | 1 | 6.79 | |
| | | | QPSK | 0.750 | 6.08 | 6.32 | 11.0 | 1 | 6.32 | |
| INBOUND | | 0.519 | | | | | | | | |
| | | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 11.86 |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 12.78 |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 14.62 |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 16.01 |
| INBOUND | | 0.842 | | | | | | | | |
| | | | 8PSK | 0.660 | 0.60 | 0.41 | 10.8 | 10 | 5.95 | 12.27 |
| | | | QPSK | 0.660 | 0.89 | 0.19 | 5.0 | 10 | 8.93 | 15.25 |
| | | 1.683 | | | | | | | | |
| | | | 8PSK | 0.660 | 1.19 | 0.83 | 21.6 | 5 | 5.95 | 12.27 |
| | | | QPSK | 0.660 | 1.78 | 0.38 | 10.0 | 5 | 8.92 | 15.24 |
| | | 2.104 | | | | | | | | |
| | | | 8PSK | 0.660 | 1.49 | 1.03 | 27.0 | 4 | 5.95 | 12.27 |
| | | | QPSK | 0.660 | 2.23 | 0.47 | 12.5 | 4 | 8.93 | 15.25 |
| | | 4.208 | | | | | | | | |
| | | | 8PSK | 0.660 | 2.97 | 2.07 | 54.0 | 2 | 5.95 | 12.27 |
| | | | QPSK | 0.660 | 4.46 | 0.95 | 25.0 | 2 | 8.93 | 15.25 |

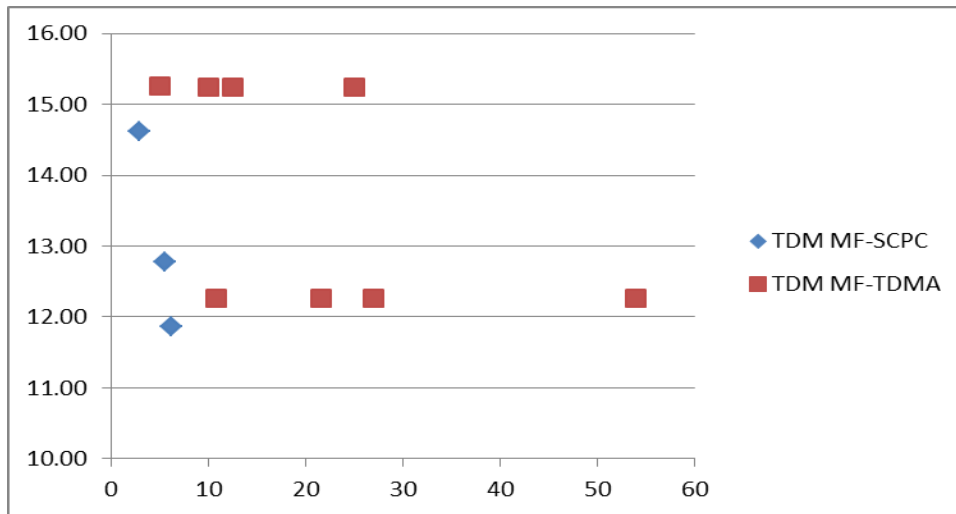


Figure 9.9: Results of 256 kbps CIR with 4:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.10. Results for 256 kbps CIR, 2:1 Oversubscription

| CIR: 256 kbps | | Oversub: 2 :1 | | | | | | | | |
|-----------------|--------------|---------------|-------|-----------|-------|-------------|----------|---------------|-----------|--|
| DIRECTION | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth | |
| | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total | |
| | | | | | | | | MHz | MHz | |
| OUTBOUND | 7.721 | | | | | | | | | |
| | | 8PSK | 0.875 | 4.12 | 31.40 | 54.4 | 1 | 31.40 | | |
| | | 8PSK | 0.75 | 4.80 | 22.59 | 39.1 | 1 | 22.59 | | |
| | | QPSK | 0.875 | 6.18 | 8.05 | 13.9 | 1 | 8.05 | | |
| | | QPSK | 0.750 | 7.21 | 7.49 | 13.0 | 1 | 7.49 | | |
| INBOUND | 0.519 | | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 13.03 | |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 13.95 | |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 15.79 | |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 17.18 | |
| INBOUND | 0.989 | | | | | | | | | |
| | | 8PSK | 0.660 | 0.70 | 0.49 | 12.7 | 10 | 6.99 | 14.48 | |
| | | QPSK | 0.660 | 1.05 | 2.23 | 5.8 | 10 | 22.31 | 29.80 | |
| | 1.995 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.41 | 0.98 | 25.6 | 5 | 7.05 | 14.54 | |
| | | QPSK | 0.660 | 2.12 | 4.50 | 11.7 | 5 | 22.50 | 29.99 | |
| | 2.494 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.76 | 1.23 | 32.0 | 4 | 7.05 | 14.54 | |
| | | QPSK | 0.660 | 2.65 | 5.63 | 14.6 | 4 | 22.50 | 29.99 | |
| | 4.988 | | | | | | | | | |
| | | 8PSK | 0.660 | 3.53 | 2.46 | 64.1 | 2 | 7.05 | 14.54 | |
| | | QPSK | 0.660 | 5.29 | 11.25 | 29.3 | 2 | 22.50 | 29.99 | |

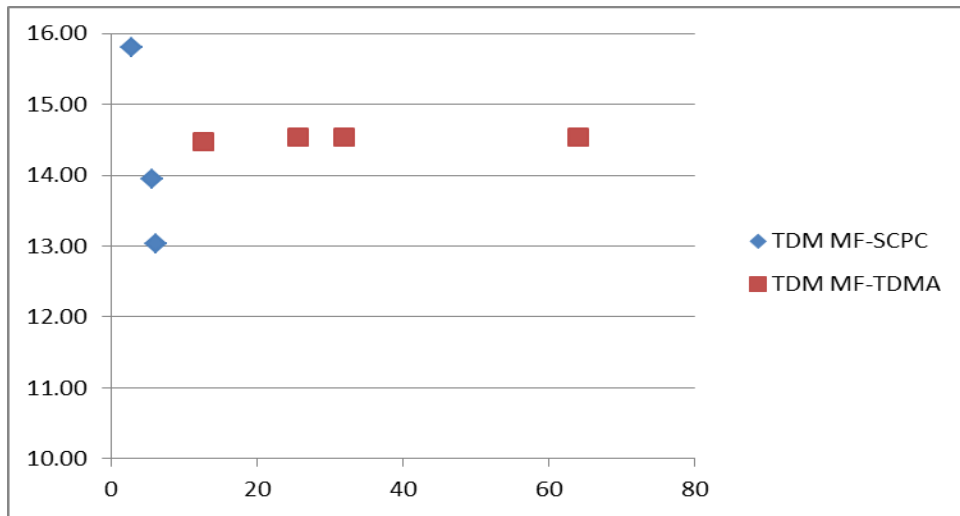


Figure 9.10: Results of 256 kbps CIR with s:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.11. Results for 384 kbps CIR, 10:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth |
|-----------------------|--------------|----------|------------|-------|-----------|-------|-------------|----------|---------------|-----------|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total |
| | | | | | | | | | MHz | MHz |
| CIR: 384 kbps | | | | | | | | | | |
| Oversub: 10 :1 | | | | | | | | | | |
| OUTBOUND | 8.204 | | | | | | | | | |
| | | | 8PSK | 0.875 | 4.38 | 33.36 | 57.8 | 1 | 33.36 | |
| | | | 8PSK | 0.75 | 5.11 | 24.00 | 41.5 | 1 | 24.00 | |
| | | | QPSK | 0.875 | 6.56 | 8.55 | 14.8 | 1 | 8.55 | |
| | | | QPSK | 0.750 | 7.66 | 7.96 | 13.8 | 1 | 7.96 | |
| INBOUND | 0.519 | | | | | | | | | |
| | | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 13.49 |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 14.42 |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 16.26 |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 17.65 |
| INBOUND | 1.06 | | | | | | | | | |
| | | | 8PSK | 0.660 | 0.75 | 0.52 | 13.6 | 10 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 1.12 | 0.24 | 6.3 | 10 | 11.24 | 19.20 |
| | 2.12 | | | | | | | | | |
| | | | 8PSK | 0.660 | 1.50 | 1.04 | 27.2 | 5 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 2.25 | 0.48 | 12.6 | 5 | 11.24 | 19.20 |
| | 2.650 | | | | | | | | | |
| | | | 8PSK | 0.660 | 1.88 | 1.30 | 34.0 | 4 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 2.81 | 0.60 | 15.8 | 4 | 11.24 | 19.20 |
| | 5.299 | | | | | | | | | |
| | | | 8PSK | 0.660 | 3.75 | 2.60 | 68.0 | 2 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 5.62 | 1.19 | 31.5 | 2 | 11.24 | 19.20 |

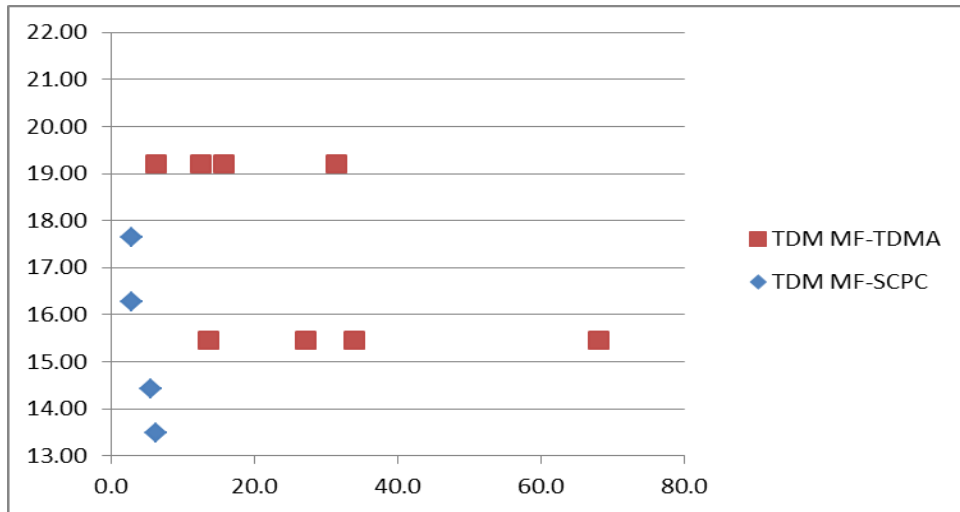


Figure 9.11: Results of 384 kbps CIR with 10:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.12. Results for 384 kbps CIR, 8:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth |
|----------------------|--------------|----------|------------|-------|-----------|-------|-------------|----------|---------------|-----------|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total |
| | | | | | | | | | MHz | MHz |
| CIR: 384 kbps | | | | | | | | | | |
| Oversub: 8 :1 | | | | | | | | | | |
| OUTBOUND | 8.204 | | 8PSK | 0.875 | 4.38 | 33.36 | 57.8 | 1 | 33.36 | |
| | | | 8PSK | 0.75 | 5.11 | 24.00 | 41.5 | 1 | 24.00 | |
| | | | QPSK | 0.875 | 6.56 | 8.55 | 14.8 | 1 | 8.55 | |
| | | | QPSK | 0.750 | 7.66 | 7.96 | 13.8 | 1 | 7.96 | |
| INBOUND | 0.519 | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 13.49 |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 14.42 |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 16.26 |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 17.65 |
| INBOUND | 1.06 | | 8PSK | 0.660 | 0.75 | 0.52 | 13.6 | 10 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 1.12 | 0.24 | 6.3 | 10 | 11.24 | 19.20 |
| | 2.12 | | 8PSK | 0.660 | 1.50 | 1.04 | 27.2 | 5 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 2.25 | 0.48 | 12.6 | 5 | 11.24 | 19.20 |
| | 2.650 | | 8PSK | 0.660 | 1.88 | 1.30 | 34.0 | 4 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 2.81 | 0.60 | 15.8 | 4 | 11.24 | 19.20 |
| | 5.299 | | 8PSK | 0.660 | 3.75 | 2.60 | 68.0 | 2 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 5.62 | 1.19 | 31.5 | 2 | 11.24 | 19.20 |

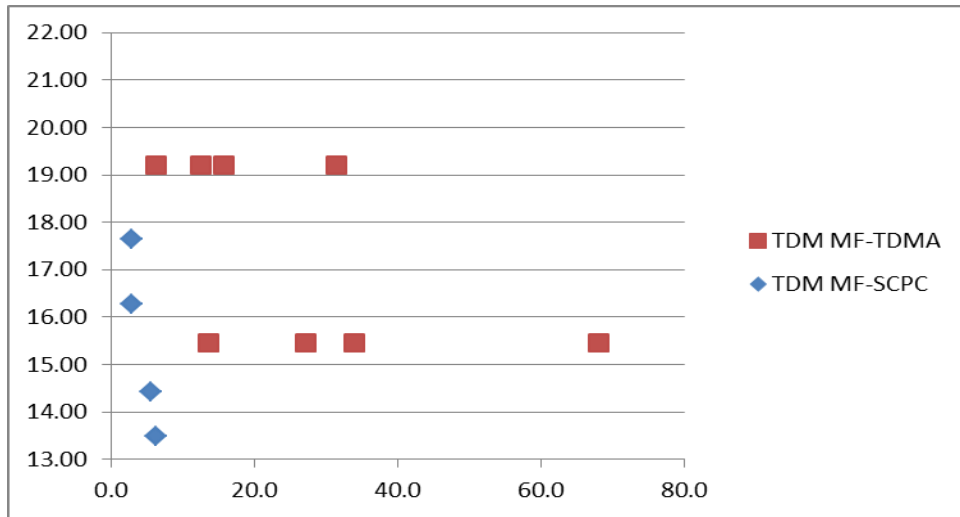


Figure 9.12: Results of 384 kbps CIR with 8:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.13. Results for 384 kbps CIR, 6:1 Oversubscription

| DIRECTION | | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth |
|-----------------|--|--|------------|-------|-----------|-------|-------------|----------|---------------|-----------|
| | | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total |
| | | | | | | | | | MHz | MHz |
| | | CIR: 384 kbps Oversub: 6 :1 | | | | | | | | |
| OUTBOUND | | 8.204 | | | | | | | | |
| | | | 8PSK | 0.875 | 4.38 | 33.36 | 57.8 | 1 | 33.36 | |
| | | | 8PSK | 0.75 | 5.11 | 24.00 | 41.5 | 1 | 24.00 | |
| | | | QPSK | 0.875 | 6.56 | 8.55 | 14.8 | 1 | 8.55 | |
| | | | QPSK | 0.750 | 7.66 | 7.96 | 13.8 | 1 | 7.96 | |
| INBOUND | | 0.519 | | | | | | | | |
| | | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 13.49 |
| | | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 14.42 |
| | | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 16.26 |
| | | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 17.65 |
| INBOUND | | 1.06 | | | | | | | | |
| | | | 8PSK | 0.660 | 0.75 | 0.52 | 13.6 | 10 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 1.12 | 0.24 | 6.3 | 10 | 11.24 | 19.20 |
| | | 2.12 | | | | | | | | |
| | | | 8PSK | 0.660 | 1.50 | 1.04 | 27.2 | 5 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 2.25 | 0.48 | 12.6 | 5 | 11.24 | 19.20 |
| | | 2.650 | | | | | | | | |
| | | | 8PSK | 0.660 | 1.88 | 1.30 | 34.0 | 4 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 2.81 | 0.60 | 15.8 | 4 | 11.24 | 19.20 |
| | | 5.299 | | | | | | | | |
| | | | 8PSK | 0.660 | 3.75 | 2.60 | 68.0 | 2 | 7.50 | 15.46 |
| | | | QPSK | 0.660 | 5.62 | 1.19 | 31.5 | 2 | 11.24 | 19.20 |

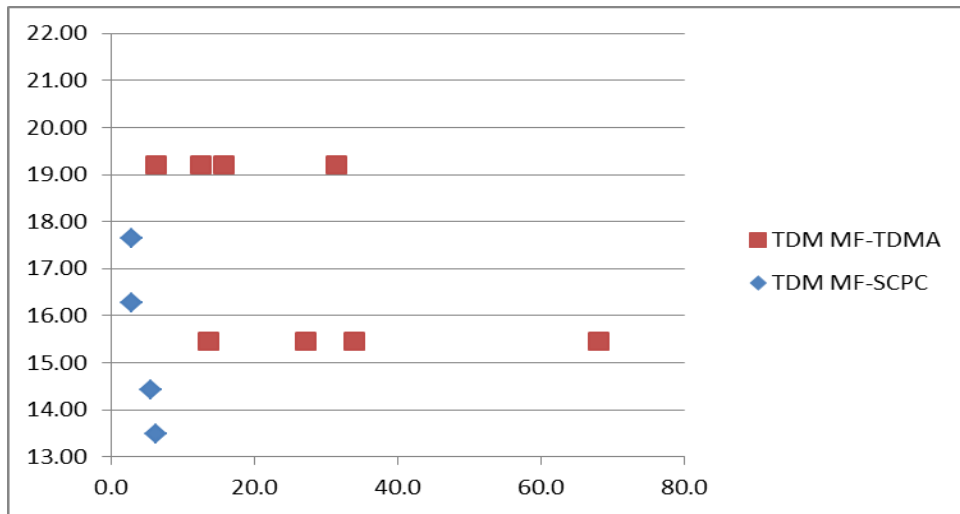


Figure 9.13: Results of 128 kbps CIR with 6:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.14. Results for 384 kbps CIR, 4:1 Oversubscription

| CIR: 384 kbps | | Oversub: 4 :1 | | | | | | | | |
|---------------|------------------|----------------------|-------------|------------------|------------|-----------------------|---------------|-----------------------------------|---------------------------|--|
| DIRECTION | Datarate Mbps | Modulation Q or 8 | FEC Rate | Allocated MHz | PEB MHz | ODU Power Watts | Carriers # | Bandwidth per Direction MHz | Bandwidth Total MHz | |
| OUTBOUND | 8.445 | | | | | | | | | |
| | | 8PSK | 0.875 | 4.51 | 34.34 | 59.5 | 1 | 34.34 | | |
| | | 8PSK | 0.75 | 5.26 | 24.71 | 42.8 | 1 | 24.71 | | |
| | | QPSK | 0.875 | 6.76 | 8.80 | 15.3 | 1 | 8.80 | | |
| | | QPSK | 0.750 | 7.88 | 8.19 | 14.3 | 1 | 8.19 | | |
| INBOUND | 0.519 | | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 13.73 | |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 14.65 | |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 16.50 | |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 17.88 | |
| INBOUND | 1.091 | | | | | | | | | |
| | | 8PSK | 0.660 | 0.77 | 0.54 | 14.0 | 10 | 7.71 | 15.90 | |
| | | QPSK | 0.660 | 1.16 | 0.25 | 6.4 | 10 | 11.57 | 19.76 | |
| | 2.182 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.54 | 1.07 | 28.0 | 5 | 7.71 | 15.90 | |
| | | QPSK | 0.660 | 2.31 | 0.49 | 12.8 | 5 | 11.57 | 19.76 | |
| | 2.728 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.93 | 1.34 | 35.0 | 4 | 7.71 | 15.90 | |
| | | QPSK | 0.660 | 2.89 | 0.62 | 16.0 | 4 | 11.57 | 19.76 | |
| | 5.455 | | | | | | | | | |
| | | 8PSK | 0.660 | 3.86 | 2.69 | 70.0 | 2 | 7.71 | 15.90 | |
| | | QPSK | 0.660 | 5.79 | 1.23 | 32.0 | 2 | 11.57 | 19.76 | |

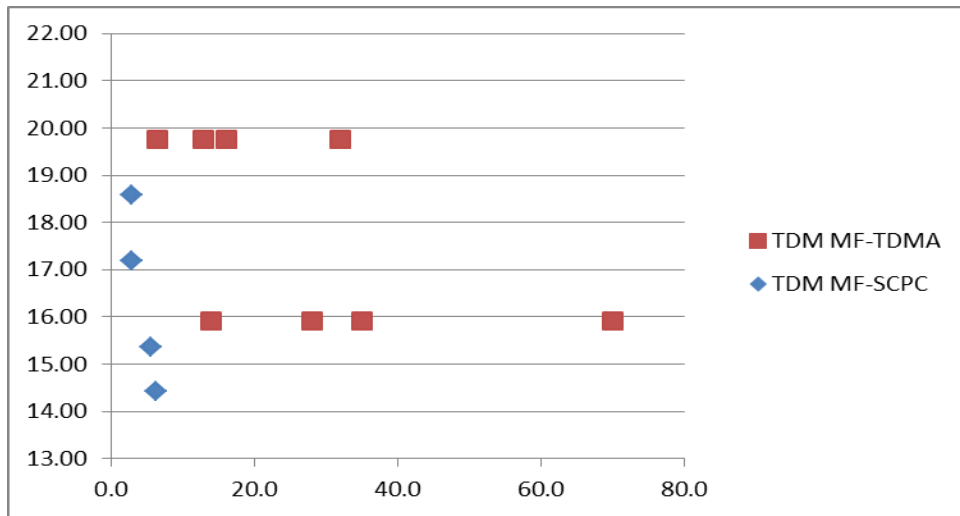


Figure 9.14: Results of 384 kbps CIR with 4:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

9.15. Results for 384 kbps CIR, 2:1 Oversubscription

| CIR: 384 kbps | | Oversub: 2 :1 | | | | | | | | |
|-----------------|--------------|---------------|-------|-----------|-------|-------------|----------|---------------|-----------|--|
| DIRECTION | Datarate | Modulation | FEC | Allocated | PEB | ODU | Carriers | Bandwidth | Bandwidth | |
| | Mbps | Q or 8 | Rate | MHz | MHz | Power Watts | # | per Direction | Total | |
| | | | | | | | | MHz | MHz | |
| OUTBOUND | 9.169 | | | | | | | | | |
| | | 8PSK | 0.875 | 4.89 | 37.29 | 64.6 | 1 | 37.29 | | |
| | | 8PSK | 0.75 | 5.71 | 26.82 | 46.4 | 1 | 26.82 | | |
| | | QPSK | 0.875 | 7.33 | 9.56 | 16.6 | 1 | 9.56 | | |
| | | QPSK | 0.750 | 8.56 | 8.89 | 15.5 | 1 | 8.89 | | |
| INBOUND | 0.519 | | | | | | | | | |
| | | 8PSK | 0.875 | 0.28 | 0.24 | 6.2 | 20 | 5.54 | 14.43 | |
| | | 8PSK | 0.75 | 0.32 | 0.22 | 5.6 | 20 | 6.46 | 15.35 | |
| | | QPSK | 0.875 | 0.42 | 0.11 | 2.9 | 20 | 8.30 | 17.20 | |
| | | QPSK | 0.750 | 0.48 | 0.11 | 2.8 | 20 | 9.69 | 18.58 | |
| INBOUND | 1.185 | | | | | | | | | |
| | | 8PSK | 0.660 | 0.84 | 0.58 | 15.2 | 10 | 8.38 | 17.27 | |
| | | QPSK | 0.660 | 1.26 | 0.27 | 7.0 | 10 | 12.57 | 21.46 | |
| | 2.369 | | | | | | | | | |
| | | 8PSK | 0.660 | 1.68 | 1.17 | 30.4 | 5 | 8.38 | 17.27 | |
| | | QPSK | 0.660 | 2.51 | 0.53 | 14.0 | 5 | 12.56 | 21.46 | |
| | 2.961 | | | | | | | | | |
| | | 8PSK | 0.660 | 2.09 | 1.46 | 38.0 | 4 | 8.38 | 17.27 | |
| | | QPSK | 0.660 | 3.14 | 0.67 | 17.5 | 4 | 12.56 | 21.46 | |
| | 5.923 | | | | | | | | | |
| | | 8PSK | 0.660 | 4.19 | 2.91 | 76.0 | 2 | 8.38 | 17.27 | |
| | | QPSK | 0.660 | 6.28 | 1.33 | 35.0 | 2 | 12.57 | 21.46 | |

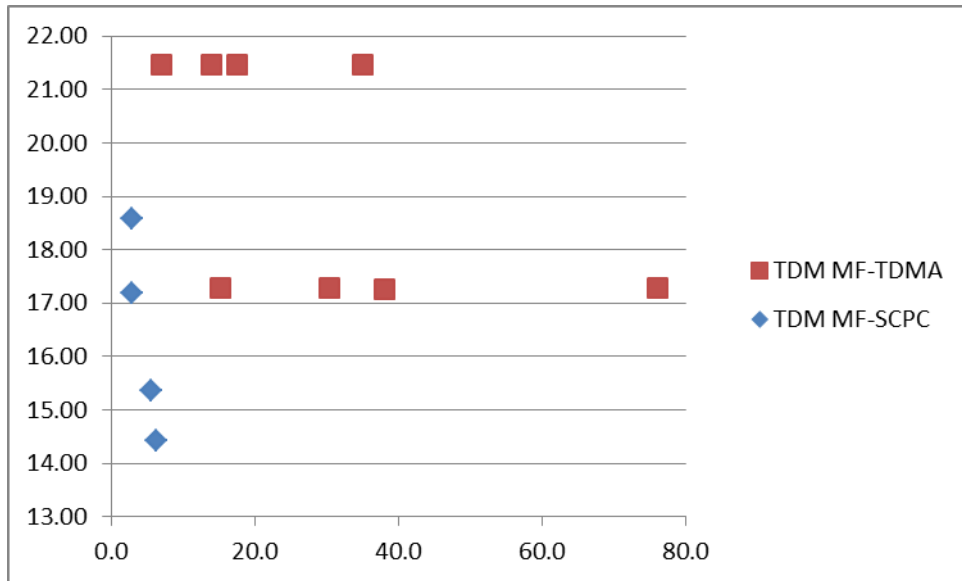


Figure 9.15: Results of 384 kbps CIR with 2:1 Oversubscription Ratio

(MHz on Vertical Axis, HPA Power on Horizontal Axis)

10. Discussion of Results and Conclusions

In reviewing the results within Section 7, several observations can be made. First, the information rate of the 20 SCPC inbounds in all traffic scenarios must be 519 kbps to allow the single remote site supported by this link to burst to 512 kbps. The fact that the maximum data rate, per site, must be allocated to all remote sites within a TDM / MF-SCPC network is the major disadvantage of this approach. Even when a remote in the network does not have data to transmit, bandwidth still needs to be set aside. The higher the CIR per site, the less of a disadvantage this would be since the traffic load would have high duty cycles and average required throughputs, over time, would be higher. Likewise, the lower the oversubscription of the burstable bandwidth, the less of a disadvantage an MF-SCPC model has. In this case, the shared bandwidth, which is the burstable data rate less the CIR, would be more frequently used.

When the different TDMA carrier sizes are compared to each other, interesting observations come to light. As discussed earlier, a shared carrier, whether it be in the outbound or the inbound direction, must be sized for the worst-case per network. While TDMA carrier sizes vary, for the case in which only two remotes are placed within a return channel, the same TDMA channel size must be used for four different 128 kbps CIR traffic mixes. While the sum of CIRs within these two remotes is only 256 kbps, the network must be designed to support a single remote to burst to 512 kbps while still supporting the CIR of the other remote, hence the requirement of a 672 kbps inbound carrier. Similar instances of this can be witnessed with the 256 kbps CIR teamed with 10:1 and 8:1 oversubscription rates (748 kbps) along with the 384 kbps CIR teamed with 10:1, 8:1 and 6:1 oversubscription rates (1.06 Mbps). The results show no

similar instances with a higher number of remotes per inbound as traffic can be shared across, 4, 5 or 10 remotes, smoothing out the bandwidth requirement.

The TDM channel does not have the limitation of the overheads of TDMA, but does have an element of overhead due to the fact that the IP frames in use utilize an MTU size of 1500. As frames are not disassembled at the hub location and reassembled at the remote site, this entire 1500 bytes must be allocated, hence to “topping out” of TDM size in the case of a 256 kbps CIR with either a 10:1 or 8:1 oversubscription ratio and a 384 kbps CIR with either a 10:1, 8:1 or 6:1 oversubscription ratio.

From an RF perspective, the more aggressive the modulation and coding pair (i.e. the higher the E_b/N_0 requirement at the remote demodulator), the less allocated bandwidth and more PEB is required. The results in Section 7 show the link budget results of all parameter combinations. While both allocated bandwidth and power equivalent bandwidth requirements are shown for all scenarios, the greater of the two is chosen for the final bandwidth requirement calculation (shown in each of the tables to the far right and also within each scatter plot. All else being equal, proper satellite link design attempts to minimize the difference between these two parameters to minimize the total transponder bandwidth that must be procured to support a given link.

As can be seen in Section 7, the best modulation and coding pair for the 20 SCPC returns is 8PSK 0.875, which requires 0.28 MHz allocated bandwidth and 0.24 MHz power equivalent bandwidth. 8PSK/0.75, QPSK/0.875 and QPSK/0.75 options require much more allocated bandwidth than Power Equivalent Bandwidth, however with lower HPA requirements (QPSK only requiring 2.8 W - 2.9 W). This aggressive modulation and FEC combination can be used due

to the large antenna used at the receive (hub) site (9.0M), which provides significant receive gain of the signal when received from the satellite.

Similarly, the TDM / MF-TDMA option can leverage this large hub antenna to use the more aggressive modulation and coding option (8PSK 0.66) in all cases. The tables of Section 7 show that the QPSK 0.66 option requires very little power on the satellite but due to the fact that only two bits are sent per Hertz, versus the three bits sent per Hertz for 8PSK, the additional bandwidth is in excess from ideal.

The best choice for the TDM outbound in all cases is QPSK with 0.75 FEC. While a more aggressive modulation and coding pair would allow for a lower allocated bandwidth requirement, the required power equivalent bandwidth increases. Perusing the different scenarios in Section 7 show that the QPSK / 0.75 option provides a very good allocated bandwidth / power equivalent bandwidth mix. The reason that this conservative modulation and coding pair is most efficient is due to the small receive antenna sizes in the field (2.4M). While a larger antenna would allow a more aggressive modulation and FEC to be used, this would require substantially more capital expenditure.

While it is true that proper RF design selects the modulation and coding that minimizes the difference between allocated and power equivalent bandwidth, higher modulation and coding rates require more transmit power at the transmit location. It is essential that all elements, both one-time purchases (hardware) and ongoing expenses (leased bandwidth) be considered to make the proper modulation and coding selection.

Using the analysis data of the return SCPC channels of Section 7 as an example, it can be seen that while the 8PSK 0.875 option requires the least total satellite resource (0.28 MHz), it

requires the largest HPA size (6.2 W). In comparison, the QPSK 0.75 option would require only 2.8 W of power at the remote but require 0.48 MHz per carrier. The other two modulation and coding options fall between these two.

The same holds true for the TDMA return channels. If one uses the 128 kbps CIR 10:1 oversubscription example, it can be seen that only 0.48 MHz is required for each of the 10 inbound carriers, 32% percent less than the amount of bandwidth required in the QPSK option (0.71 MHz). However, while the QPSK option requires only 4.0 W of power, the 8PSK option requires more than double this, 8.6 W to close the link.

There is another hardware element that must be addressed when comparing and contrasting satellite network designs; the hardware required to support each link in the network at each site. Sticking with the 128 kbps CIR 10:1 oversubscription example, if one compares the remote site power requirements of the TDM / MF-SCPC option (range of 2.8 W – 6.2 W) to the range of TDM / MF-TDMA power requirements of the ten (10) carrier scenario (4.0 W-8.6 W), there does not exist much difference. However, in the two (2) carrier scenario, either 13.0 W (QPSK option) or 27.9 W (8PSK option) are required at each remote site. If one were to select only based upon bandwidth, which is the 8PSK option in both cases, it would be necessary to equip each of the 20 remote sites with HPAs of more than four times the size of the SCPC option (27.9 W vs. 6.2 W). The takeaway here is that the larger the carrier, the better the sharing of bandwidth across remotes but also the greater the power requirement per site. This capital expenditure difference required to equip remotes increases as the size of the network (number of sites) increases. For smaller networks, this is not as much of an issue.

A review of the scatter plots, which show the total amount of bandwidth required for the network on the vertical axis and the total HPA power required on the horizontal axis, proves the concepts addressed in this thesis:

- In almost all cases, the hardware requirement of the TDM / MF-SCPC options is lower than all TDM-MF-TDMA options. The two main reasons for this are the better performance characteristics of the TDM / MF-SCPC modem under study teamed with the size of carrier.
- The higher the CIR, the more attractive the TDM / MF-SCPC option is versus the TDM / MF-TDMA option.
- The higher the oversubscription ratio, the more attractive the TDM / MF-TDMA option is versus the TDM / MF-SCPC option.

The best solution for each of the fifteen (15) scenarios depends on how one wishes to balance the total required bandwidth and the total required power at each remote site. If a network is to be limited in operational expenditures, one would choose the option that minimizes the satellite resource (MHz). If a network is to be limited in capital expenditures, one would choose the option that minimizes the size of the HPAs in the field. Also, there are often power limitations at remote sites, especially in remote areas (for example, Nigeria, which is the location used in this study) so it may not be possible to provide enough voltage via solar panels or other means to run large HPAs in the field.

In practice, the most common approach is to perform a Total Cost of Ownership (TCO) analysis for the life of a project, taking into account both operational and capital expenditures. The option with the lowest TCO is most often chosen, although other factors come into play as well, including providing the ability for growth by “oversizing” a remote kit to “future-proof” a network.

In closing, a one-size-fits-all solution for any and all traffic mixes or any and all constraints does not exist. It is the hope of the author that this thesis provided the reader with an overview of the many elements that are involved in geosynchronous satellite point-to-multipoint Internet Protocol (IP)-based multimedia communications design, bringing home these concepts with a real-life example.

11. Areas of Additional Research

Due to its large scope, this thesis has covered many elements that each could warrant its own study. Because of this, there are several areas of additional research that could be undertaken to gather a much more in depth knowledge in any one area, particularly satellite payload and/or antenna design, RF link budget analysis, multimedia IP traffic and loading characteristics, satellite access technologies (MCPC, TDM, FDMA, TDMA, etc.), and/or a deep dive into the mechanics of the many Forward Error Correction (FEC) techniques referenced within this study.

Also, the IP network sizing tool could be used in tandem with the LST-5 link budget tool to address many more use cases as a finite number of fifteen (15) combinations of CIR (128kbps, 256kbps, 384kbps) and oversubscription (2:1, 4:1, 6:1, 8:1, 10:1) were analyzed within this study with all remote sites having the same traffic profile. Different combinations of CIR and oversubscription could be also analyzed while the BIR could also be made variable to determine how this variable changes the outcomes.

From a network design perspective, a different number of sites in different locations using different satellites and different antenna sizes could also be undertaken as these were held constant throughout the comparative analysis. Also, while the satellite beam under question uses C-band frequencies, further study could undertake the analysis of Ku-band or Ka-band frequencies, teamed with, potentially Adaptive Coding and Modulation (ACM), which allows for a carrier to switch modulation and coding, per burst, depending upon varying link conditions.

The Low-Density Parity Check (LDPC), which has recently come into commercial acceptance and moderate market uptake, provides an increased level of coding gain over TPC. Further research can be done in this field to determine what savings, in terms of bandwidth and transmit power, could be achieved with this coding technique.

Lastly, commercial satellite communications platforms are starting to be introduced that allow the dynamic allocation of SCPC channels. In this study, and until the advent of this technology throughout commercial practice, static SCPC return channels are used. The use of the dynamic SCPC method may lead to the best of both worlds, allowing a satellite network design engineer to size around the worst case per site, as is allowed when utilizing SCPC, while also providing a means to share bandwidth, which is available with TDMA.

Bibliography

(Aha) Comtech AHA Corporation, "Primer: Turbo Product Codes"

(Ber1) Berrou, Claude, Alain Glavieux and Punya Thitimajshima. "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo-Codes", *ICC '93*, Geneva, Switzerland, May 1993, pp. 1064-1070.

(Ber2) Berrou, Claude and Alan Glavieux. "Near Optimum Error Correcting Coding and Decoding: Turbo-Codes", *IEEE Transactions on Communications*, Vol.44, pp. 1261-1271. October, 1996.

(Bos) Bose, R.C. and Ray-Chaudhuri, D.K. "On a class of Error Correcting Binary Group Codes", *Information and Control*, Vol.3, pp. 68-79, March 1960.

(Gag) Gagliardi, Robert M., "Satellite Communications", Second Edition

(Gor) Gorenstein, D. and Zierler, N. "A Class of Error Correcting Codes in p^m Symbols", *Journal of the Society of Industrial and Applied Mathematics*, Vol. 9, pp. 207-214, June 1961.

(Ham) Hamming, R. W. 1950. "Error Detecting and Error Correcting Codes", *Bell System Technical Journal*, Vol. 29, pp. 147-160.

(Hoc) Hocquenghem, A. "Codes Correcteurs d-erreurs", *Chiffres*, Vol.2, pp. 147-156, 1959.

(Hug) Hughes, C. D., C. Soprano, F. Feliciani, and M. Tomlinson, 1993. "Satellite systems in a VSAT environment," *Electronics and Communications Engineering Journal*, vol. 5, no. 5 October, pp. 285-291.

(Mar) G. Maral, *VSAT Networks*, John Wiley & Sons, Ltd., Chichester, England, 1995.

(Nil) <http://www.nilesat.com.eg/Nilesat%20GT%20Enlarge.htm>

(Pet) Peterson, W. W. "Encoding and Error-Correction Procedures for the Bose-Chaudhuri Codes", *IRE Transactions on Information Theory*, Vol. IT-6, pp. 459-470, September 1960.

(Pra) Pratt, Timothy and Charles W. Bostian, *Satellite Communications*, John Wiley & Sons, Ltd., New York, 1986.

(Mar) G. Maral, *VSAT Networks*, John Wiley & Sons, Ltd., Chichester, England, 1995.

(Ran) Rana, Hamid A., J. McCoskey and W. Check, 1990. "VSAT Technology, Trends, and Applications," *Proceedings IEEE*, vol. 78, no. 7, July, pp. 1087-1095

(Ree) Reed, I.S. and Solomon, G. "Polynomial Codes Over Certain Finite Fields", *SIAM Journal of Applied Mathematics*, Vol. 8, pp. 300-304, 1960.

(Rod) Roddy, Dennis. 1995. *Satellite Communications Second Edition*. New York: McGraw-Hill.

(Sun) Sun, Zhili. 2005. *Satellite Networking, Principles and Protocols*. West Sussex: John Wiley & Sons, Ltd.

(Vit) Viterbi, A.J. "Error bounds for convolutional codes and an asymptotically optimal decoding algorithm", *IEEE Transactions on Information Processing*, 13: pp. 260-269, 1967.

(Wic) Wicker, Stephen B. 1995. *Error Control Systems for Digital Communication and Storage*.
Upper Saddle River: Prentice-Hall Inc.