On Minimizing WGS Transponder Power by Optimizing Channel Gains Designed for Uplink Frequency Reuse via Circular Polarization

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***Abstract*—The Wideband Global SATCOM system (WGS) satellite has the unique means to set sub-channel (SC) gain for a specific link or bandwidth segment. Certain Ka-band antennas can switch to an orthogonal circular polarization (CP) to use the identical frequencies more than once in the same geographic location. This allows planners to boost total capacity in an area of operations (AOR) without adding assigned bandwidth. The unique properties of CP make estimating cross-polarization interference (XPI) difficult. The concern of XPI is the extra expenditure of satellite resources. This paper shows a method to mitigate uplink XPI. It will show a method to determine the channel gain as a function of uplink SNR, intermodulation (IM) noise, and uplink XPI. This paper builds on previous works from Marshall [1], Knab [2], and Gonzalez [7].**

I. INTRODUCTION

Department of defense (DoD) satellites have resources that must be optimized to satisfy all mission requirements. Optimal performance is realized when the best possible signal-to-noise ratio (SNR) is achieved and the expenditure of satellite resources, which are subject to the constraints of the earth terminal (ET) types, is minimized. Previous work derived the electronic gain for the WGS satellite [1-5]. These papers accounted for channel loading and the impact of a nonlinear channel. In this paper, we will refine the work in [2] by considering XPI. We will show that minimizing satellite power is accomplished by maximizing uplink SNR whenever channel gains and bandwidth can be set for the link. Reference [7] developed a concept of achievable uplink SNR for a given XPI and link spectral efficiency. This work showed that on its own, the MIL-STD-188-164B specification is incomplete for frequency reuse, because the link XPI is difficult to predict. Before looking at the XPI challenges, the paper will provide a method to calculate the satellite transfer gain (STG) to minimize the expenditure of satellite resources as a function of uplink SNR.

II. OVERVIEW

Typical transponder satellites receive multiple uplink signals and retransmits these signals in direct proportion to the uplink SNR. The satellite transmit power, typically expressed as $EIRP$, which stands for effective isotropic radiated power, has two components. We can define the composite satellite $EIRP$ for a specific link to be a the sum of these two components: the S = signal-$EIRP$ and N = noise-$EIRP$ as:

$$EIRP_{S,N} = STG\left(S_r + N_0 BW\right). \tag{1}$$

Where S_r is the received signal power at the satellite interface, N_0 is the equivalent noise power spectral density $(kT_S)^1$ at the satellite interface, BW stands for bandwidth, and STG is the satellite-transfer-gain, which is defined as the end-to-end gain to include the electronic-gain plus the antenna gain in the direction of the transmitting and receiving ET. Equation 1 can be re-written as a function of uplink SNR as

$$EIRP_{S,N} = EIRP_S + \frac{EIRP_S}{\left(\frac{C}{N}\right)_{up}}. \tag{2}$$

Where $(C/N)up$ is the uplink SNR. Equations 1, and 2 show that the composite $EIRP_{S,N}$ is both a function of $(C/N)up$ and STG. For most satellites, the transponder BW is fixed, and the STG can only take on one value. The uniqueness of the WGS design is the link BW can be any value from 2.6 MHz to 125 MHz in 2.6 MHz increments. Each SC can have a unique gain assigned to it. For example, the link can be assigned 5 SC for a total BW of 13 MHz, with a unique gain-state (GS). Hence, the biggest and most important design distinction between WGS and most other transponder satellites is that link $EIRP_{S,N}$ has two independent controls: BW and gain.

This paper postulates that the optimal uplink SNR for WGS is 22 dB. Hence, the optimal $(C/N_0)_{up}$ over the entire 125 MHz channel is 103 dBHz. [2] So, a 22 dB uplink SNR corresponds to $(C/N_0)_{up}$ of 86.2 dBHz in one SC. Consequently, the optimal $(C/N_0)_{up}$ as a function of the number SC can be determined by equation 3

$$\left(\frac{C}{N_0}\right)_{up} = 86.2 + 10\log_{10}\left[\chi\right]. \tag{3}$$

Here, $(C/N_0)_{up}$ in dBHz, is the uplink carrier power-to-noise-power-spectral-density ratio and χ is an integer from 1 to 48 representing the number of SC. Equation 3 computes the equivalent uplink SNR of 22 dB for any number of SC creating

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[1] The effective (kT) at the interface of the satellite is $\frac{k}{G/T_s}$.

[2] Throughout this paper SNR and (C/N_0) will be used interchangeably, when BW becomes a major design constraint the proper variable will be addressed.

the carrier BW. With the uplink goal established, this fact about positive numbers

$$\frac{ab}{a+b} \leq \min\left\{a, b\right\}$$

provides the following insight about the achievable satellite link SNR. The achievable SNR cannot be greater than the uplink SNR. This is because the achievable SNR is equal to the product over the sum of the uplink and downlink SNR. Hence, the achievable SNR is always less than or equal to established uplink SNR. Adding interference components exacerbate this. Thus, any satellite link SNR can be considered as a percentage of the uplink SNR. This leads to Equation 4, which determines the link data rate (DR).

$$DR_{link} = \frac{\left(\frac{C}{N_0}\right)_{up} X}{\left(\frac{E_b}{N_0}\right)}. \tag{4}$$

Where X is a percent value $0 \leq X \leq 1$ and E_b/N_0 is the required operating point with an added margin to meet the mission-availability. From equation 4, it follows that:

$$\left(\frac{C}{N_0}\right)_R = DR\frac{E_b}{N_0} = X\left(\frac{C}{N_0}\right)_{up}. \tag{5}$$

Throughout, $(C/N_0)_R$ will denote the overall satellite-link SNR.

The WGS STG can be calculated as

$$STG = \frac{(G_r)\,G\,(G_t)}{g(z)}, \tag{6}$$

where G_r is the WGS receive antenna gain towards the transmitting ET, and G_t is the transmit antenna gain of the WGS towards the receiving ET. The factor $g(z)$ is the small signal gain compression and is a function of z, where z represents the composite drive level which is derived in [1]. Finally, G is the transponder/channel electronic gain, which is comprised of the electronic gain from the input of the LNA to the output of the HPA.

The factor G can be adjusted for common and unique signals. The channelizer provides the means to set unique gain states (GS) for signals. The channelizer has a 50 dB gain range, $-10\,\text{dB} \leq GS \leq 40\,\text{dB}$. Equation 1 can be modified to calculate the composite satellite $EIRP_{S,N}$ for a specific link for WGS as

$$EIRP_{S,N} = STG\left[\left(\frac{C}{N_0}\right)_{up} + \beta\chi\right]\frac{k}{\frac{G}{T_S}}, \tag{7}$$

where $\beta = 2.6MHz$, $\frac{G}{T_s}$ is the satellite receiver figure of merit towards the transmitting ET, k is Boltzmann's constant,[3] and χ was defined above. Equation 7, shows how the WGS link $EIRP_{S,N}$ can have two independent controls: BW and gain.

From [2] the end-to-end $(C/N_0)_R$ can be re-written using typical satellite variables as

$$\left(\frac{C}{N_0}\right)_R = \frac{GG_t\frac{G}{T_e}kT_s\left(\frac{C}{N_0}\right)_{up}}{G_tkT_sG\frac{G}{T_e} + \gamma\frac{G}{T_e} + kl_d}, \tag{8}$$

where $\frac{G}{T_e}$ is the receiving ET figure of merit, G and G_t were defined above, T_S is the system noise temperature of the WGS Ka-beam pointed at the transmitting ET, and γ is defined in [1]. Equation 9 allows us to determine the electronic gain, G, for the link as

$$G = \frac{\left(\frac{C}{N_0}\right)_R\left[\left(\frac{G}{T_e}\right)\gamma + kl_d\right]}{G_t\left(\frac{G}{T_e}\right)kT_s\left[\left(\frac{C}{N_0}\right)_{up} - \left(\frac{C}{N_0}\right)_R\right]}. \tag{9}$$

The term γ accounts for intermodulation (IM) noise power spectral density (PSD) EIRP. It is another source of independent white Gaussian noise. Note the IM noise EIRP is not included in the satellite EIRP because it is assumed that it is generated independently by the amplifier. Reference [1] developed equations for IM noise PSD as a function of drive level z. The Boeing specification for IM noise is given as a noise power ratio (NPR) and is specified as 16.5 dB at the nominal operating point (NOP). Using the parameters of [1], figure 1 is a plot that relates the drive level to the Boeing NPR. The drive level at NOP can be used to calculate $g(z)$ using [1]. It should be noted that Knab did not include the effects of small-signal suppression $g(z)$, as detailed by Marshall. As such, Knab used a static NPR value and Marshall expressed NPR as a function of drive-level. The remainder of this paper does not account for $g(z)$, however, without loss of accuracy, small-signal suppression can be incorporated. By substituting equation 5 into equation 9, we can express G as a function of X

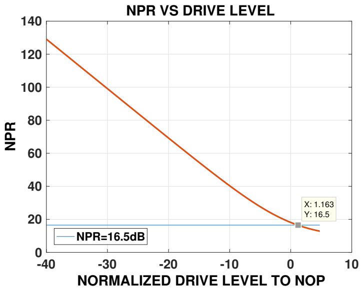

Fig. 1: Drive-Level vs. NPR

$$G = \frac{\left[\left(\frac{G}{T_e}\right)\gamma + kl_d\right]}{G_t\left(\frac{G}{T_e}\right)kT_s}\left[\frac{X}{1-X}\right]. \tag{10}$$

Note the highest value of X must be slightly <100%. Figure 2 plots the rational function $[(X)/(1-X)]$. The plot of G will have the similar shape as figure 2 but scaled by the terms in equation 10. When $(C/N_0)_R$ is 50% of the uplink SNR, which is the case when the uplink and downlink are equal, the rational function is 0 dB. Consequently, all links that fall under 50%, G are reduced, all links over 50% G must be increased by the values in figure 2. Increasing G, increases

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[3] $1.38 \times 10^{-23} J/K$