WIRELESS COMMUNICATIONS DESIGN HANDBOOK

Aspects of Noise, Interference, and Environmental Concerns

VOLUME 1: SPACE INTERFERENCE

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Chapter 6 | Noise Representations in Transponders and Multiple Access

6.0 Introduction

At the heart of a satellite communications system is the transponder. The transponder consists of input and output filters, up and down converters, phase-locked loops, and traveling wave tube amplifiers (TWTAs.) More modern transponders systems are using solid state power amplifiers (SSPAs). We now consider the nonlinear behavior of the transponder. A block diagram representation of a typical transponder was shown in Figure 5.36.

Let the input of the transponder be represented by

$$S_{\mathrm{i}}(t) = A\cos(\omega_{\mathrm{c}}t + f(\theta)), \tag{6.1}$$

where $\omega_{\mathrm{c}} = 2\pi f_{\mathrm{c}}$ is the angular carrier frequency and phase of the input signal. The transponder output can be represented as

$$S_{\mathrm{out}} = g(A)\cos(\omega_{\mathrm{c}}t + f(\theta) + f(A)). \tag{6.2}$$

If $g(A)$ and $f(A)$ are independent of ω_{c}, let $A_k(t)$, $\omega_{\mathrm{c}} + \omega_k$, and $f(\theta_k(t))$ denote the envelope, the angular carrier frequency, and the phase of the kth carrier. ω_{c} is the midband frequency or center frequency, which can take any value within a transponder bandwidth. For m number of modulated carriers, access to a transponder input can be represented by

$$\begin{aligned} S_{\mathrm{i}}(t) &= \sum_{k=1}^{m} A_k(t)\cos\{(\omega_{\mathrm{c}} + \omega_k)t + f_k(\theta(t)\} = \left[\sum_{k=1}^{m} A_k(t)\cos(\omega_k t + f_k(\theta(t))\right]\cos\omega_{\mathrm{c}}t \\ &\quad - \left[\sum_{k=1}^{m} A_k(t)\sin(\omega_k t + f_k(\theta(t))\right]\sin\omega_{\mathrm{c}}t \\ &= X(t)\cos\omega_{\mathrm{c}}t - Y(t)\sin\omega_{\mathrm{c}}t = \sqrt{X^2 + Y^2}\cos\left[\omega_{\mathrm{c}}t + \tan^{-1}\frac{Y}{X}\right] \\ &= \mathrm{Re}\left\{\sqrt{X^2 + Y^2}\exp\left[j\omega_{\mathrm{c}}t + j\tan^{-1}\left(\frac{Y}{X}\right)\right]\right\}. \end{aligned} \tag{6.3}$$

The corresponding transponder output is

$$\begin{aligned} S_{\text{out}}(t) &= \text{Re}\left\{ g(\sqrt{X^2+Y^2}) \cdot \exp\left[j\omega_c t + \tan^{-1}\left(\frac{Y}{X}\right) + jf(\sqrt{X^2+Y^2}) \right] \right\} \\ &= \text{Re}\left\{ g(\sqrt{X^2+Y^2}) \cdot \exp\left[jf(\sqrt{X^2+Y^2}) \right] \frac{(X+jY)}{\sqrt{X^2+Y^2}} \exp(j\omega_c t) \right\}. \end{aligned} \tag{6.4}$$

Define the double Fourier transform

$$L(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{g(\sqrt{X^2+Y^2})}{\sqrt{X^2+Y^2}} \exp\left[jf(\sqrt{X^2+Y^2}) \right] (X + jY) \exp[-juX - jvY]\, dx\, dy,$$

which means

$$g(\sqrt{X^2+Y^2}) \exp\left[jf(\sqrt{X^2+Y^2}) \right] \frac{(X+jY)}{\sqrt{X^2+Y^2}} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} L(u, v) \exp[juX + jvY]\, du\, dv.$$

Therefore,

$$S_{\text{out}}(t) = \frac{1}{(2\pi)^2} \text{Re}\, [\exp(j\omega_c t) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} L(u, v) \exp[juX + jvY]\, du\, dv].$$

After further mathematical manipulations,

$$S_{\text{out}}(t) = \text{Re}\left\{ \exp(j\omega_c t) \sum_{K_1=-\infty}^{\infty} \sum_{K_2=-\infty}^{\infty} \cdots \sum_{K_n=-\infty}^{\infty} \exp\left[\begin{matrix} jK_1(\omega_1 t + f(\theta_1)) + jK_2(\omega_2 t + f(\theta_2)) \\ + \ldots + jK_n(\omega_n t + f(\theta_n)) \end{matrix} \right] \cdot N(k) \right\},$$

where $K_1, K_2, \ldots, K_n$ can be zero or any integers either positive or negative, and

$$\begin{aligned} N(k) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \frac{g(\sqrt{X^2+Y^2})}{\sqrt{X^2+Y^2}} \exp[jf(\sqrt{X^2+Y^2})](X+jY) \prod_{\ell=1}^{m} J_{K_\ell}(A_\ell \sqrt{u^2+v^2}) \\ \times \exp\left[j \sum_{\ell=1}^{m} K_\ell \tan^{-1} \frac{u}{v} \right] \exp[-jux - jvy]\, dx\, dy\, du\, dv, \end{aligned} \tag{6.5}$$

where J_K is the Kth-order Bessel function. Using the polar coordinate transformation

$$X = \rho \cos \xi, \qquad u = \gamma \sin \eta$$
$$Y = \rho \sin \xi, \qquad v = \gamma \cos \eta$$

and performing the integration on ξ and η simplifies the expression to the following two cases. For $K_1 + K_2 + \ldots + K_n = 1$,

$$N(k) = \int_0^\infty \int_0^\infty \gamma \prod_{\ell=1}^{m} J_{K\ell}(A_\ell \gamma)\, \rho\, g(\rho) \exp(jf(\rho)) \cdot J_1(\gamma \rho)\, d\gamma\, d\rho$$

and for $K_1 + K_2 + \ldots + K_n \neq 1, \qquad N(k) = 0.$

Finally, the output of the transponder can be expressed as

$$S_{\text{out}}(t) = \text{Re}\{N(k) \exp[j(\overline{\omega}\, t + f_{\bar{\ell}}(\theta)]\}, \tag{6.6}$$

where

$$f_{\bar{\ell}}(\theta) = \sum_{\ell=1}^{m} K_\ell f_\ell(\theta)$$

$$\overline{\omega} = \omega_c + \sum_{\ell=1}^{m} K_\ell\, \omega_\ell.$$

In the case of numerical computation, the factor $g(\rho)\exp[jf(\rho)]$ can be approximated by

$$g(\rho)\exp[jf(\rho)] = \sum_{\ell=1}^{L} b_\ell J_1(\alpha \ell \rho),$$

where L is the number of coefficients needed, J_1 is the first-order Bessel function, and $\alpha = 2\pi/$(period of the Fourier series). For a given transponder, the characteristics $g(\rho)$ and $f(\rho)$ are known. Since $g(\rho)$ and $f(\rho)$ are given, the coefficients b_ℓ can be obtained by an approximation, and $N(k)$ reduces to

$$N(k) = \sum_{\ell=1}^{L} b_\ell \prod_{\ell=1}^{m} J_{K_\ell}(\alpha \ell A_\ell), \tag{6.7}$$

which outlines the amplitude for each input signal. The b_ℓ are determined by best fit from the input data of $g(\rho)$ and $f(\rho)$ in terms of least-square error. Computer programs can calculate $S_{\text{out}}(t)$ when $S_i(t)$, $g(\rho)$, and $f(\rho)$ are given.

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