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基于对消解调的时相调制误码率分析*

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摘 要:以二进制为例,从对消解调的角度,导出了时相调制(TPM)信号在加性白高斯噪声信道下的误码率解析表达式。可以发现:TPM 信号误码率与码元突变后的波形持续时间成反比,即相同信噪比条件下持续时间越长则误码率越小。通过对比判决统计量,可以发现对消解调是相关解调的简洁实现方式。仿真结果验证了上述理论推导。其结论可为进一步分析时相调制的其他解调方法性能提供参照和依据。

关键词:超窄带;时相调制;相位突变;对消解调;匹配滤波

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Analysis of Bit Error Rate of Time-phase Modulation Based on Demodulation after Cancellation

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Abstract:The analytic expression of bit error rate(BER) is derived following the route of demodulation after cancellation when binary modulation is accepted in the channel of Gauss white noise. It can be found that the BER of time – phase modulation(TPM) is inversely proportional to the code duration after phase jump,that is to say, the longer the duration is, the smaller the BER on condition that the same signal – to – noise ratio(SNR) is kept. Through the comparison of decision variable, it can be found that demodulation after cancellation is the concise version of correlation demodulation. The simulations verify the theoretical derivation, which can provide the reference and basis for further analysis of other demodulation performance of time-phase modulation.

Key words:ultra narrow band;time-phase modulation;phase jump;demodulation after cancellation;matched filter

1 引 言

20 世纪 80 年代,美国的 H.R. Walker 等人开始致力于一种被称之为超窄带(UNB)的调制技术研究,相继提出了可变相移键控 (VPSK)[1]、甚小频移键控(VMSK)[2]和脉冲位置相位翻转键控(3PRK)[3]调制技术。UNB 传输不可思议的性能也引起了国内学者的注意,并开展跟踪研究。2004 年,吴乐南教授提出了甚小波形差键控(VWDK)调制[4]。由于 VWDK 受到波形差异的限制,其解调非常困难,解调

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性能也较差,在实际中很难实现。随后在 2006 年,吴乐南教授提出了扩展的二元相移键控(EBPSK)调制[5]。该调制方法是对 UNB 中的脉冲位置相位翻转键控的扩展,因此其实质仍属于相位突变调制。王红星教授从离散时间与相位突变相结合的角度出发,将相位突变调制重新定义为时相调制(TPM),并着重研究了 TPM 信号的非平稳特性和相应的滤波、解调方法[6-9],给出了误码率仿真结果。但是,尚未从理论上进行误码率表达式的推导。本文在 TPM 定义基础上,以二进制为例,从对消解调的角度,导出了 TPM 信号在加性白高斯噪声信道下的误码率表达式。通过对比相关解调和对消解调的判决统计量可以发现,对消解调实质上是相关解调的另一种实现方式。仿真验证了上述理论推导。

2 时相调制

2.1 定义

相位突变调制是由 H.R. Walker 提出的利用矩形脉冲快速的下降或上升边缘特性进行相位调制的一种载波调制技术。与常规数字调制方式相比,最大的区别在于将通信系统的承载信息与时变信号相联系,进一步丰富了调制信号的可调参量。在此基础上的时相调制信号定义如下[6]:

$$s(t)=A\cos(\omega_c t+\varphi(t_m,\Delta t)) \tag{1}$$

式中,$\varphi(t_m,\Delta t)$表示已调信号的相位在 t_m时刻发生相位突变,并且相位突变后波形持续时间为 Δt,即:

$$\varphi(t_m,\Delta t)=\begin{cases}\theta, & 0\leqslant t<t_m,\ t_m+\Delta t\leqslant t<T\\ \theta+\Delta\varphi, & t_m\leqslant t\leqslant t_m+\Delta t\end{cases} \tag{2}$$

式中,$\Delta\varphi$ 为相位突变角,T 为码元周期。不失一般性,可将二进制的 TPM 信号定义为

$$s(t)=\begin{cases}s_0(t), & \text{发送 0 码}\\ s_1(t), & \text{发送 1 码}\end{cases},0\leqslant t\leqslant T \tag{3}$$

其中:

$$s_0(t)=A\cos(2\pi f_c t+\theta_1),0\leqslant t\leqslant T$$

$$s_1(t)=\begin{cases}A\cos(2\pi f_c t+\theta_1),0\leqslant t\leqslant \tau\\ A\cos(2\pi f_c t+\theta_2),\tau<t\leqslant T\end{cases}$$

式中,f_c表示载波频率,τ 表示一个码元周期内的相位突变时刻。以单极性不归零码的二进制 TPM 波形为例,给出 TPM 波形表达式为

$$s_n(t)=\sum_{n=1}^{N}[a_n\cdot s_1(t-nT)+(1-a_n)\cdot s_0(t-nT)] \tag{4}$$

其中,a_n表示码元序列,N 为码元数目。图 1 为码元序列[1 1 0 1 0]的 TPM 信号波形,码元传输速率为 1.5 Mbit/s,载波频率为30 MHz。

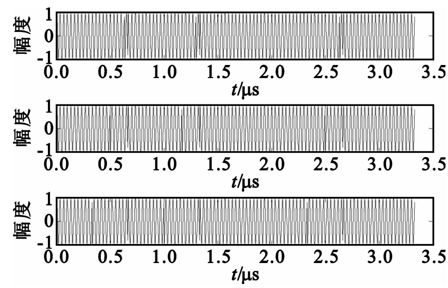

图 1 TPM 信号波形图(从上至下的调制码元突变时刻依次为脉宽的 19/20、15/20、10/20 倍)
Fig.1 TPM signal waveform (the phase jump lies at 19/20, 15/20, and 10/20 of pulse-width from top to bottom)

2.2 对消解调

TPM 信号的相关接收如图 2 所示,在此基础上可以得到对消解调方案。

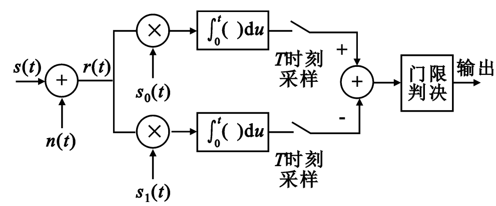

图 2 相关解调示意图
Fig.2 Correlation demodulation

以发送 0 码的已调信号 $s_0(t)$为参考信号,对已调信号 $s(t)$进行对消,可以得到对消后的波形为

$$\tilde{s}(t)=\begin{cases}0, & \text{发送 0 码}\\ \tilde{s}_1(t), & \text{发送 1 码}\end{cases},0\leqslant t\leqslant T \tag{5}$$

其中:

$$\tilde{s}_1(t)=s_1(t)-s_0(t)=$$

$$\begin{cases}0, & 0\leqslant t\leqslant\tau\\ A[\cos(2\pi f_c t+\theta_2)-\cos(2\pi f_c t+\theta_1)], & \tau<t\leqslant T\end{cases} \tag{6}$$

可以发现:在发送 0 码时,对消后无信号,而发送 1 码时,则会存在残差。因此,可以利用该残差信息来进行相关解调,如图 3 所示。

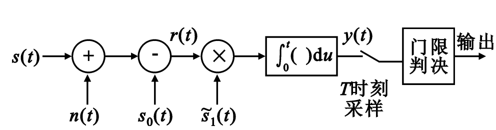

图 3 对消解调示意图
Fig.3 Demodulation after cancellation

3　误码率

从式(6)可以看出,残差越明显则越有利于解调,因此,不妨取 $|\theta_2-\theta_1|=\pi$,则对消后的二进制已调波为

$$\tilde{s}_n(t) = \sum_{n=1}^{N} a_n \cdot \tilde{s}_1(t-nT) \tag{7}$$

其中:

$$\tilde{s}_1(t)=\begin{cases}0, & 0\leqslant t\leqslant \tau\\ 2A\cos(2\pi f_c t+\theta_2), & \tau<t\leqslant T\end{cases}$$

在加性白高斯噪声信道中,接收信号为

$$r(t)=\tilde{s}_n(t)+n(t) \tag{8}$$

式中,$n(t)$的单边功率谱密度为 n_0。对式(8)所示信号进行匹配接收,此匹配滤波器的冲激响应为

$$h(t)=\tilde{s}_1(T-t),\quad 0\leqslant t\leqslant T \tag{9}$$

当发送 1 码时,该码元周期内的匹配滤波器输出为

$$y(t) = \int_0^t r(u)h(t-u)\mathrm{d}u \tag{10}$$

则 $t=T$ 时刻的匹配滤波器输出为

$$y(t)|_{t=T} = \int_0^T [\tilde{s}_1(u)+n(u)]\tilde{s}_1(u)\mathrm{d}u = \int_0^T \tilde{s}_1^2(u)\mathrm{d}u + \int_0^T n(u)\tilde{s}_1(u)\mathrm{d}u = E_s + N_s \tag{11}$$

式中,N_s是高斯随机变量,其条件均值为零,条件方差为 $n_0E_s/2$。将$y(t)|_{t=T}$用y_T表示,则

$$p(y_T|\tilde{s}_1) = \frac{1}{\sqrt{\pi n_0 E_s}}\mathrm{e}^{-\frac{(y_T-E_s)^2}{n_0E_s}} \tag{12}$$

当发送 0 码时,$t=T$ 时刻的匹配滤波器输出为

$$y(t)|_{t=T} = \int_0^T n(u)\tilde{s}_1(u)\mathrm{d}u = N_s \tag{13}$$

则有

$$p(y_T|0) = \frac{1}{\sqrt{\pi n_0 E_s}}\mathrm{e}^{-\frac{y_T^2}{n_0E_s}} \tag{14}$$

以最小错判概率准则进行检测,其误码率计算公式如下:

$$p_r = p(\tilde{s}_1)\cdot\int_{-\infty}^{\xi} p(y_T|\tilde{s}_1)\mathrm{d}y_T + p(0)\cdot\int_{\xi}^{+\infty} p(y_T|0)\mathrm{d}y_T \tag{15}$$

取最佳门限为 $\xi=E_s/2$[10],那么

$$p_r = 0.5\cdot\int_{-\infty}^{E_s/2} p(y_T|\tilde{s}_1)\mathrm{d}y_T + 0.5\cdot\int_{E_s/2}^{+\infty} p(y_T|0)\mathrm{d}y_T = \int_{-\infty}^{E_s/2} p(y_T|\tilde{s}_1)\mathrm{d}y_T = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_s}{4n_0}}\right) = Q\left(\sqrt{\frac{E_s}{2n_0}}\right) \tag{16}$$

上式即为加性白高斯噪声信道下的对消解调误码率解析表达式。根据式(7),$E_s=2A^2(T-\tau)$,则

$$p_r = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{2A^2(T-\tau)}{4n_0}}\right) = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{A^2T}{2n_0}\cdot\frac{(T-\tau)}{T}}\right) = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_b}{n_0}\cdot\frac{(T-\tau)}{T}}\right) = Q\left(\sqrt{\frac{E_b}{n_0}\cdot\frac{2(T-\tau)}{T}}\right) \tag{17}$$

式中,E_b表示对消前的 TPM 信号平均比特能量,即:

$$E_b = \left[\int_0^T s_0^2(t)\mathrm{d}t + \int_0^T s_1^2(t)\mathrm{d}t\right]/2 = A^2T/2 \tag{18}$$

根据上述的对消解调方案,可以得到当发送 0 码时判决统计量为

$$E_s/2 - \int_0^T [s_0(t)+n(t)-s_0(t)]\cdot[s_1(t)-s_0(t)]\mathrm{d}t = \int_0^T (s_0^2(t)-s_0(t)s_1(t))\mathrm{d}t - \int_0^T n(t)[s_0(t)-s_1(t)]\mathrm{d}t \tag{19}$$

当发送 1 码时判决统计量为

$$E_s/2 - \int_0^T [s_1(t)+n(t)-s_0(t)]\cdot[s_1(t)-s_0(t)]\mathrm{d}t = \int_0^T (s_0(t)s_1(t)-s_1^2(t))\mathrm{d}t + \int_0^T n(t)[s_0(t)-s_1(t)]\mathrm{d}t \tag{20}$$

根据图 2 所示的相关解调方案,设判决门限为 0,则当发送 0 码时判决统计量为

$$\int_0^T [s_0(t)+n(t)]\cdot[s_0(t)-s_1(t)]\mathrm{d}t - 0 = \int_0^T (s_0^2(t)-s_0(t)s_1(t))\mathrm{d}t + \int_0^T [s_0(t)-s_1(t)]n(t)\mathrm{d}t \tag{21}$$

当发送 1 码时判决统计量为

$$\int_0^T [s_1(t)+n(t)]\cdot[s_0(t)-s_1(t)]\mathrm{d}t - 0 = \int_0^T (s_0(t)s_1(t)-s_1^2(t))\mathrm{d}t + \int_0^T [s_0(t)-s_1(t)]n(t)\mathrm{d}t \tag{22}$$

对比上述两者的判决统计量可知完全相同,因此,对消解调实质上是相关解调的另一种实现方式。

4 仿真

仿真条件为:码元传输速率为1.5 Mbit/s,载波频率为30 MHz,采样频率为300 MHz。图 4 ~ 6 给出了不同码元突变时刻的误码率曲线图,其中 3 条曲线分别对应于对消解调误码率、不对消的相关解调误码率和理论推导的误码率,可以看出三者的结果极为接近。这也证明了对消解调和相关解调的误码率性能是一致的,式(16)和式(17)所示的误码率也就是加性白高斯噪声信道下的相关(匹配)接收误码率表达式。

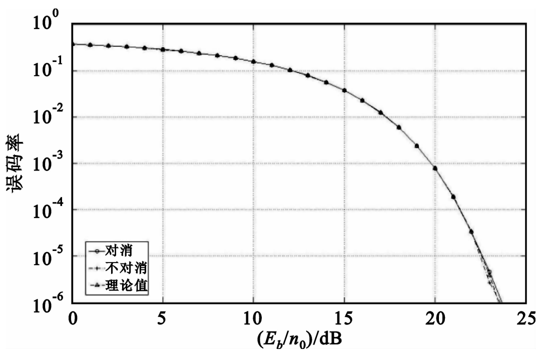

图 4 码元突变时刻为码元周期的 19/20 倍
Fig.4 The phase jump lies at 19/20 of pulse-width

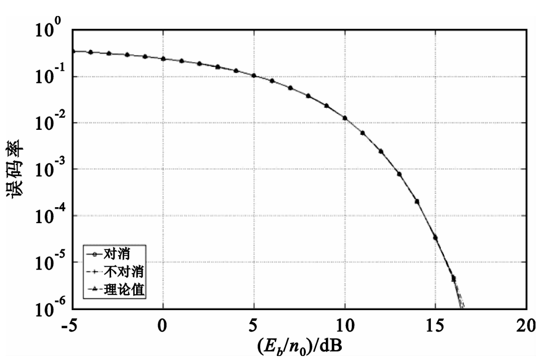

图 5 码元突变时刻为码元周期的 15/20 倍
Fig.5 The phase jump lies at 15/20 of pulse-width

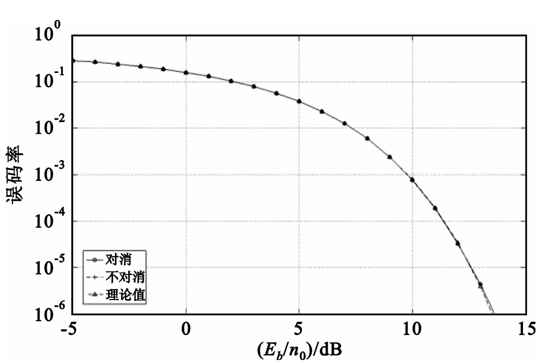

图 6 码元突变时刻为码元周期的 10/20 倍
Fig.6 The phase jump lies at 10/20 of pulse-width

5 结 论

时相调制是一种超窄带调制技术,具备很高的频带利用率。本文提出了 TPM 的对消解调方案,并以二进制为例,导出了 TPM 信号在加性白高斯噪声信道下的误码率表达式,可以发现:TPM 信号误码率与码元突变后的波形持续时间成反比,即相同信噪比条件下持续时间越长则误码率越小。

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