

AD-A213 949

DTIC  
REPORT DOCUMENTATION PAGE

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |                                              |                                                                                                       |                                                         |                                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|----------------------------------------------|-------------------------------------------------------------------------------------------------------|---------------------------------------------------------|--------------------------------------------------|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |       |                                              | 1b. RESTRICTIVE MARKINGS                                                                              |                                                         |                                                  |
| 2a. SECURITY CLASSIFICATION AUTHORITY<br>OCT 30 1989                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |       |                                              | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br><br>Approved for public release; distribution is unlimited. |                                                         |                                                  |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |       |                                              | 5. MONITORING ORGANIZATION REPORT NUMBER(S)                                                           |                                                         |                                                  |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |       |                                              | 7a. NAME OF MONITORING ORGANIZATION                                                                   |                                                         |                                                  |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Naval Ocean Systems Center                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |       | 6b. OFFICE SYMBOL<br>(If applicable)<br>NOSC | 7b. ADDRESS (City, State and ZIP Code)                                                                |                                                         |                                                  |
| 6c. ADDRESS (City, State and ZIP Code)<br>San Diego, California 92152-5000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |       |                                              | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER                                                       |                                                         |                                                  |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>Space and Naval Warfare Systems Command                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |       | 8b. OFFICE SYMBOL<br>(If applicable)         | 10. SOURCE OF FUNDING NUMBERS                                                                         |                                                         |                                                  |
| 8c. ADDRESS (City, State and ZIP Code)<br>Washington, DC 20363-5100                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |       |                                              | PROGRAM ELEMENT NO.<br>OMN                                                                            | PROJECT NO.<br>CM19                                     | TASK NO.<br>AGENCY<br>ACCESSION NO.<br>DN587 543 |
| 11. TITLE (include Security Classification)<br>BANDWIDTH EFFICIENT SYNCHRONOUS TUNING (BEST) FOR IMPROVED VERY-LOW-FREQUENCY AND LOW-FREQUENCY (VLF/LF) COMMUNICATIONS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |       |                                              |                                                                                                       |                                                         |                                                  |
| 12. PERSONAL AUTHOR(S)<br>P. M. Hansen, R. W. Middlestead                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |       |                                              |                                                                                                       |                                                         |                                                  |
| 13a. TYPE OF REPORT<br>presentation/paper                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |       | 13b. TIME COVERED<br>FROM TO                 |                                                                                                       | 14. DATE OF REPORT (Year, Month, Day)<br>September 1989 |                                                  |
| 15. PAGE COUNT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |       |                                              |                                                                                                       |                                                         |                                                  |
| 16. SUPPLEMENTARY NOTATION                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |       |                                              |                                                                                                       |                                                         |                                                  |
| 17. COSATI CODES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |       |                                              | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)                     |                                                         |                                                  |
| FIELD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | GROUP | SUB-GROUP                                    |                                                                                                       |                                                         |                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |                                              | communications                                                                                        |                                                         |                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |                                              | high voltage                                                                                          |                                                         |                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |                                              | corona                                                                                                |                                                         |                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |                                              | propagation                                                                                           |                                                         |                                                  |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number)<br><br>Synchronously tuning a transmit antenna to the instantaneous tones of a frequency modulated waveform can result in enormous improvements in radiated power efficiency and data detection. The best performance is obtained when the modulation waveform tones are phase continuous and when the maximum tone separation is much smaller than the operating frequency. Both of these conditions are satisfied by most systems. The advantages in using Bandwidth Efficient Synchronous Tuning (BEST) are realized by a significant reduction in the loss and distortion effects usually associated with fixed tuned antennas. This paper characterizes the performance of continuous-phase frequency-shift-keying (FSK) and minimum-shift-keying (MSK) modulated waveforms with synchronous tuning of the transmit antenna. Analysis and computer simulation results support the conclusion that there is less than 0.5 dB degradation in the bit-error-probability performance for instantaneous antenna bandwidths(B) several orders of magnitude less than the modulation bandwidth (1/T). Also, the radiated power can be increased by as much as 7 dB, for time-bandwidth (BT) products as low as 0.3, through the elimination of the flat loss and amplitude distortion usually associated with fixed tuned antennas. |       |                                              |                                                                                                       |                                                         |                                                  |
| Published in <i>Applied Organometallic Chemistry</i> , (1989) 3 171-176.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |       |                                              |                                                                                                       |                                                         |                                                  |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br><input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |       |                                              | 21. ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED                                                  |                                                         |                                                  |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>P. M. Hansen                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |       |                                              | 22b. TELEPHONE (include Area Code)<br>(619) 553-4187                                                  |                                                         | 22c. OFFICE SYMBOL<br>Code 832                   |

89 10 30 011

Bandwidth Efficient Synchronous Tuning (BEST)  
for Improved Very-Low-Frequency and Low-Frequency  
(VLF/LF) Communications

Richard W. Middlestead  
Telecommunication Science Associates, Inc.  
San Diego, CA 92103

Peder M. Hansen  
Naval Ocean Systems Center  
San Diego, CA 92152

Abstract

Synchronously tuning a transmit antenna to the instantaneous tones of a frequency modulated waveform can result in enormous improvements in radiated power efficiency and data detection. The best performance is obtained when the modulation waveform tones are phase continuous and when the maximum tone separation is much smaller than the operating frequency. Both of these conditions are satisfied by most systems. The advantages in using Bandwidth Efficient Synchronous Tuning (BEST) are realized by a significant reduction in the loss and distortion affects usually associated with fixed tuned antennas. This paper characterizes the performance of

continuous-phase frequency-shift-keying (FSK) and minimum-shift-keying (MSK) modulated waveforms with synchronous tuning of the transmit antenna. Analysis and computer simulation results support the conclusion that there is less than 0.5 dB degradation in the bit-error-probability performance for instantaneous antenna bandwidths(B) several orders of magnitude less than the modulation bandwidth (1/T). Also, the radiated power can be increased by as much as 7 dB, for time-bandwidth (BT) products as low as 0.3, through the elimination of the flat loss and amplitude distortion usually associated with fixed tuned antennas.

Bandwidth Efficient Synchronous Tuning (BEST)  
for Improved Very-Low-Frequency and Low-Frequency  
(VLF/LF) Communications

Richard W. Middlestead  
 Telecommunication Science Associates, Inc.  
 San Diego, CA 92103

Peder M. Hansen  
 Naval Ocean Systems Center  
 San Diego, CA 92152

### Abstract

This paper characterizes the performance of continuous-phase frequency-shift-keying (FSK) and minimum-shift-keying (MSK) modulated waveforms with synchronous tuning of the transmit antenna. Analysis and computer simulation results support the conclusion that there is less than 0.5 dB degradation in the bit-error-probability performance for instantaneous antenna bandwidths(B) several orders of magnitude less than the modulation bandwidth (1/T). Also, the radiated power can be increased by as much as 7 dB.

The practical advantages associated with synchronously tuning a high-Q transmit antenna have been known and explored for many years (refs. 1 and 2). These efforts have concentrated principally on very-low-frequency (VLF) applications for U.S. Navy submarine communications and in particular have focused on various techniques for tuning the large, high-power antennas. The technical problems associated with the switching of high power and physically large tuning elements are still being investigated. These continuing efforts are necessary to keep pace with the development of the high power solid-state amplifier technology.

### I. Introduction

Bandwidth efficient synchronous tuning (BEST) is an antenna tuning technique, applied at the transmit site, for reducing the loss and distortion of a signal radiated by a narrow bandwidth antenna. Synchronous tuning means that the resonant frequency of the transmit antenna is tuned to the instantaneous frequency of the modulated signal waveform. The analysis undertaken in this paper focuses on ideally modulated discrete frequency waveforms like M-ary Frequency-Shift-Keying (FSK) and Minimum-Shift-Keying (MSK). An example of the antenna tuning in the frequency domain is shown in Figure 1 for an ideally modulated binary-FSK waveform having a unity modulation index. In this situation, the modulation tone separation is  $\Delta f = R_b$ , where  $R_b$  is the modulation data rate.

The antenna switches to the lower modulation tone position (the dashed curve) as determined by the tuning control voltage. For binary-FSK and MSK, the minimum duration that the antenna is tuned to any tone is  $T_b = R_b^{-1}$  seconds. More generally, for M-ary FSK this duration is the symbol duration  $T = T_b \log_2(M)$ . The time-bandwidth product BT (or  $BT_b$ ) is a convenient parameter with which to characterize various performance measures.

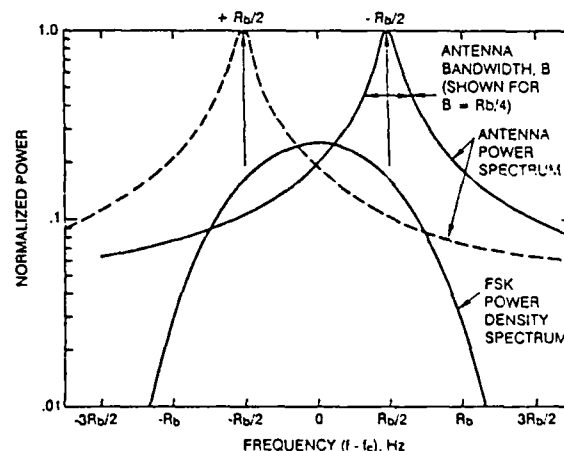


Figure 1. Relationship Between Binary-FSK Signal Spectrum and the Synchronously Tuned Antenna Frequency Response

### II. Background

In this section, the various system losses are characterized for an MSK modulated  $kI$  waveform with data rate  $1/T_b$  using a conventional fixed tuned transmit antenna. The resulting losses will serve as a

For

☒  
☐  
☐

tion

DTIC  
 COPY  
 INSPECT

|                    |                      |
|--------------------|----------------------|
| By                 |                      |
| Distribution/      |                      |
| Availability Codes |                      |
| Dist               | Avail and/or Special |
| A-1                | 20                   |

background to dramatize the potential performance advantages of synchronous antenna tuning developed in the following sections. Because the antenna is tuned to a fixed frequency, it can be conveniently modeled by the equivalent baseband transfer function expressed as

$$H(\mu) = \frac{K}{1 + j \left( \frac{2\mu}{B} \right)} \quad (1)$$

where  $\mu = f - f_c$  is the equivalent lowpass frequency,  $f_c$  is the center frequency, which is the same as the modulation carrier frequency, and  $B$  is the two-sided 3 dB bandwidth in Hz. The various sources of performance loss are the fixed loss, the receiver detection loss resulting from intersymbol interference (ISI), and the power back-off loss. The losses are shown in Fig. 2 for the fixed tuned antenna.

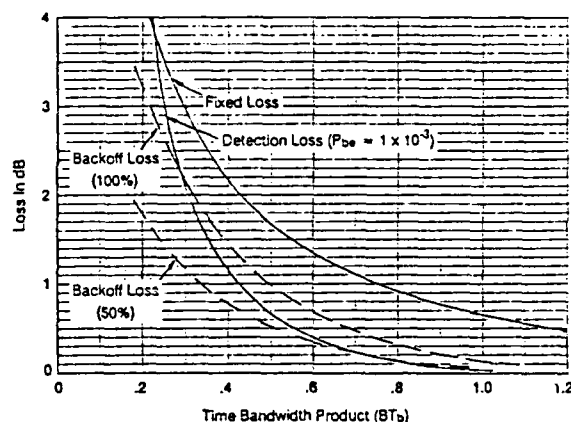


Figure 2. Various Power Losses Associated with an MSK Modulated Waveform through a Fixed Tuned Transmit Antenna

### III. Synchronous Antenna Tuning

From the results of the preceding section, it is clear that enormous communication system performance penalties can result from fixed tuned narrowband transmit antennas operating with sufficiently low  $BT_b$  products. In this section, the various sources of degradation are revisited in the context of synchronous antenna tuning. The analysis applies to a modulation waveform consisting of an arbitrary number of discrete tones as described by

$$e_i(t) = A \cos(\omega_c t + \bar{\omega}_i t + \theta_i) \quad (2)$$

where  $A$  establishes an arbitrary signal amplitude,  $\omega_c$  represents the average carrier angular frequency of the tone set

$\{\omega_i = \omega_c + \bar{\omega}_i\}$ ,  $\bar{\omega}_i$  is the instantaneous

baseband angular frequency of the modulation, and  $\theta_i$  represents a phase angle, which has a data dependent component for MSK. For the various forms of modulation considered, the transition between the frequencies is assumed to be instantaneous, thus the synchronous antenna tuning is not considered for a variety of so called tamed frequency modulated waveforms.

The antenna circuit is modeled, as in the preceding section, as a single-time-constant series tuned RLC circuit. The synchronous tuning is achieved by appropriately changing the circuit inductance  $L_i$ . The synchronous antenna tuning results in a linear time-varying circuit which is, at best, difficult to model in terms of baseband functions. In the frequency domain, the antenna is described by the dynamic system function

$$H_i(\omega; t) = \frac{2}{R} \frac{j\omega\alpha_i}{(j\omega + \alpha_i)^2 + \beta_i^2} \quad (3)$$

The subscript  $i$  denotes the time dependence of the various antenna parameters. In particular,

$\beta_i^2 = \nu_i^2 - \alpha_i^2$ , where  $\nu_i = \sqrt{1/L_i C}$  is the resonant angular frequency of the antenna and  $\alpha_i = R/2L_i$  is the one-sided 3 dB bandwidth of the antenna. Under ideal tuning conditions,  $\nu_i$  is exactly given by  $\nu_i = \omega_i$ , so that  $\beta_i^2 = \omega_i^2 - \alpha_i^2$ .

For this analysis the solution is formulated in terms of state variables, which are particularly appropriate because the coefficients are constant over discrete time intervals. The differential equation of the antenna circuit model is given by

$$\ddot{q}(t) + 2\alpha_i \dot{q}(t) + \nu_i^2 q(t) = \frac{2\alpha_i}{R} e_i(t)$$

The state variables are defined in terms of the circuit charge,  $q(t)$ , as

$$X_1(t) = q(t) \text{ and } X_2(t) = \dot{q}(t).$$

To evaluate the radiated signal strength from the antenna, it is necessary to evaluate the antenna current given by  $i(t) = X_2(t)$ .

The result is

$$i(\tau) = C X(\tau) \quad (5)$$

where  $C = (0 \ 1)$  is the output coupling vector and  $X(\tau)$  is the system state vector given by

$$X(\tau) = \phi(\tau, t_{i-1}) X(t_{i-1}) + \int_{t_{i-1}}^{\tau} \phi(\tau, \zeta) B(\zeta) e_i(\zeta) d\zeta \quad (6)$$

$$\tau \geq t_{i-1}$$

In equation 6,  $\phi(\tau, t)$  is the state transition matrix and

$$B(\tau) = B_i = \left( 0 \ \frac{2\alpha_i}{R} \right)^T$$

is the input coupling vector. Equation 6 relates the change in the system state vector with time relative to the conditions at time  $t = t_{i-1}$ . In this regard, the first term represents the initial condition response and the second represents the forced response which is characterized by the superposition integral. To evaluate the response of the synchronously tuned antenna, advantage is taken of the time invariance of the coefficients over discrete intervals  $[t_{i-1}, t_i] = [iT - T, iT]$ , in which case equation 6 involves the simplified convolutional integral and is formulated as

$$i_i(\tau) = C X_i(\tau) \quad (7)$$

$$X_i(\tau) = \phi_i(t_{i-1} - \tau) X_i(t_{i-1}) + \int_{t_{i-1}}^{\tau} \phi_i(\tau - \zeta) B_i e_i(\zeta) d\zeta \quad (8)$$

with  $t_{i-1} \leq \tau \leq t_i$ . In the remainder of this section, the characteristics of an isolated frequency transition are developed, followed by a general situation involving random contiguous frequency transitions in the modulation waveform.

#### a. Isolated Frequency Transition

In examining the transient results of an isolated frequency transition in the

modulation waveform, considerable insight is obtained regarding the impact of various signal and antenna parameters, such as the data rate, modulation index, carrier phase continuity, operating frequency, and the antenna instantaneous bandwidth. For convenience, the isolated frequency transition is taken to occur at  $t_{i-1} = t_0 = 0$ . The details are too involved for this paper, however, the resulting signal at a distant receiver can be expressed as

$$e_r(t) = \sqrt{2P_r} \cos(\omega_1 t + \phi_1) \quad (9)$$

$$0 \leq t \leq T$$

$$+ \sqrt{2P_r} M_1 e^{-\pi B t} \sin(\omega t_1 + \phi_1)$$

where  $P_r$  is an arbitrary received power level and the distortion parameters  $M_1$  and  $\phi_1$  are given by

$$M_1 = \left\{ \left[ 2 \sin(\phi_0 + \phi_\Delta/2) \sin(\phi_\Delta/2) \right]^2 + \left[ 2 \left[ \cos(\phi_0 + \phi_\Delta/2) - \frac{BT}{2} \left[ \frac{R_s}{f_c} \right] \sin(\phi_0 + \phi_\Delta/2) \right] \sin(\phi_\Delta/2) + \left[ \frac{\Delta f_1}{f_c} \sin(\phi_0) \right]^2 \right]^{1/2} \right\} \quad (10)$$

In equation 10  $\phi_0$  is the phase at  $t_0 = 0$  of the forcing function applied prior to  $t_0 = 0$  and the angle  $\phi_\Delta = \phi_1 - \phi_0$  represents the phase difference between the forcing functions at the instant of the transition. Continuous phase modulation waveforms require that  $\phi_\Delta = 0$ .  $\Delta f_1 = f_1 - f_0$  is the change in the tuning frequency in Hz. Using  $B$  instead of  $B_i$  and  $f_c$  instead of  $f_i$  are convenient substitutions which do not materially affect the results as long as the instantaneous carrier are much greater than either  $B_i$  or  $\Delta f_i$ .

The impact of the various parameters on the received signal is examined in terms of the normalized received energy-per-symbol which is given by

$$\frac{E_s}{E'_s} = \frac{1}{E'_s} \int_0^T e_r^2(t) dt \quad (12)$$

$$= 1 - \frac{2M_1}{\pi BT} (1 - e^{-\pi BT}) \sin(\phi_0 + \phi_\Delta - \phi_1) \quad (13)$$

where  $E'_S$  is the received energy-per-symbol without any distortion.

In addition to having CPM, it is desirable to operate under conditions for which  $\Delta f_1/f_c$  and  $BT$  result in a low symbol energy loss. To quantify the affect of these various parameters for CPM, the worst case loss is examined, which is seen from equation 13 to occur when  $\phi_0 = 90^\circ$ . Thus, evaluating equation 13 for  $\phi_\Delta = 0^\circ$  and  $\phi_0 = 90^\circ$  results in

$$\left. \frac{E'_S}{E_S} \right|_{\phi_\Delta = 0, \phi_0 = 90^\circ} = 1 - 2 \frac{(\Delta f_1/f_c)}{\pi BT} (1 - e^{-\pi BT}) \quad (14)$$

Equation 14 is plotted in Fig. 3 as a function of  $BT$  for various conditions of the normalized parameters  $\Delta f_1/f_c$ .

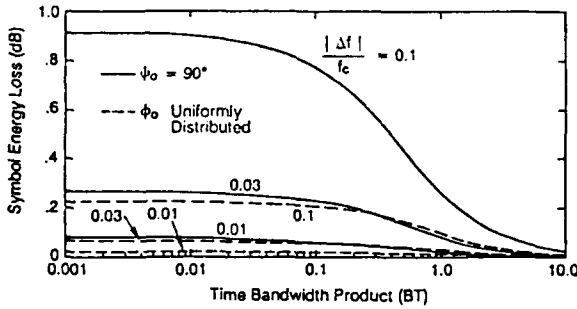


Figure 3. Maximum Symbol Energy Loss for Isolated Transition with CPM ( $\phi_\Delta = 0$ ,  $\phi_0 = 90^\circ$  and  $\Delta f_1 > 0$ ) and Continuous Phase Binary-FSK Modulation ( $\phi_\Delta = 0$ ,  $\phi_0$  uniformly distributed)

#### b. Multiple Frequency Transitions

The transient characteristics of the synchronously tuned antenna are now examined for the frequency modulated waveform consisting of multiple frequency transitions at discrete times  $t = t_i = iT$ ,  $i = 0, 1, 2, \dots$ . The details in characterizing the expression for the signal at a distant receiver are too involved to present in this paper. However, using the same initial conditions as for the isolated frequency transition, the received

signal during the  $N$ -th symbol interval can be expressed as

$$e_r(\tau) = \sqrt{2P_r} \left\{ \left[ 1 - (M_A - M_B) e^{-\pi B\tau} \right] \cos(\phi'_0) + M_C e^{-\pi B\tau} \sin(\phi'_0) \right\} \cos(\omega_N \tau) - \sqrt{2P_r} \left\{ \left[ 1 - \left( \frac{\Delta f_N}{f_c} \right) + M_A + M_B \right] e^{-\pi B\tau} \right\} \sin(\phi'_0) + M_C e^{-\pi B\tau} \cos(\phi'_0) \sin(\omega_N \tau) \quad (15)$$

where the distortion terms  $M_A$ ,  $M_B$ , and  $M_C$ , involving various waveform and antenna parameters, are similar to equation 10 developed for the isolated transition.

The phase angle  $\phi'_0$  is expressed in terms of the initial phase angle  $\phi_0$  as

$$\phi'_0 = \phi_0 + \sum_{j=1}^{N-1} \omega_j T \quad (16)$$

Because  $\phi_0$  is taken to be a uniformly distributed angle between  $-\pi$ ,  $\pi$ , the angle  $\phi'_0$  is a similarly distributed random variable. Proceeding as before and considering the uniformly distributed phase angle  $\phi_0$  in which case  $M_B = M_C = 0$ , the average received symbol energy is determined to be

$$\frac{E'_S}{E_S} = 1 - 2M'_A \left( \frac{1 - e^{-\pi BT}}{\pi BT} \right) \quad (17)$$

where, the distortion factor  $M'_A$  is given by

$$M'_A = M_A + \frac{\Delta f_N}{2f_c} \quad (18)$$

$$= \sum_{i=1}^{N-1} \left[ \frac{\Delta f_i}{2f_c} \right] e^{-\pi(N-i)BT} \quad (19)$$

Because of the dependence of  $\Delta f_i$  upon the random source data, the factor  $M'_A$  is itself a discrete random variable.

The problem now is reduced to describing a useful closed form expression

for equation 19 for a modulation waveform of interest. In this regard, the remaining discussion is specialized for binary-FSK modulation.

#### c. Multiple Frequency Transitions (Binary-FSK)

Specializing the discussion to binary-FSK waveform modulation, equation 19 can be expressed as

$$M_A' = \frac{|\Delta f|}{2f_c} \sum_{i=1}^N D_i e^{-\pi(N-i)BT_b} \quad (20)$$

where  $T = T_b$  is the bit duration and  $D_i = (1, 0, -1)$  is a zero mean, tri-state, discrete random variable. For the purpose of approximating the loss in performance, the received energy-per-bit will be defined as

$$\frac{E_b}{E_b} = 1 - \sigma_s \quad (21)$$

where  $\sigma_s$  is the standard deviation of the normalized bit energy. By examining the joint statistics of  $D_i D_j$  and evaluating the standard deviation  $\sigma_s$ , it is found that

$$\frac{E_b}{E_b} = 1 - \frac{|\Delta f|}{\sqrt{2} f_c} \left( \frac{1}{1 + e^{-\pi BT}} \right)^{1/2} \left( \frac{1 - e^{-\pi BT}}{\pi BT} \right) \quad (22)$$

Equation 22 is also plotted in Fig. 3 as a function of BT and several values of  $|\Delta f|/f_c$ .

The results are truly impressive when one considers that the modulated signal is being passed through an antenna with an instantaneous bandwidth several orders of magnitude less than that of the signal.

#### IV. Simulation Results

To support the results of the preceding analysis, the synchronously tuned antenna is modeled as a sampled data filter and evaluated using binary FSK and MSK waveform modulations. In deriving the antenna circuit model for the simulation program, advantage is taken of the fact that the antenna looks like a time-invariant network over some finite time interval. The simulation model implements the response described by equation 8. In this context, the state transition matrix projects the output response from one sample to another and the initial conditions

are constantly updated at the sampling instants.

The simulation model is used to simulate the performance of non-coherently detected binary-FSK waveform modulation having unity modulation index, i.e.  $\Delta f = R_b$ . The degradation at  $P_{be} = 10^{-3}$  is about 0.1 dB, which is about 0.1 dB less than that predicted from Fig. 3.

#### V. Conclusions

The analysis and simulation results demonstrate that synchronous antenna tuning offers significant performance gains over fixed tuned antenna systems. Fig. 4 summarizes the results as a function of the BT product for MSK modulation.

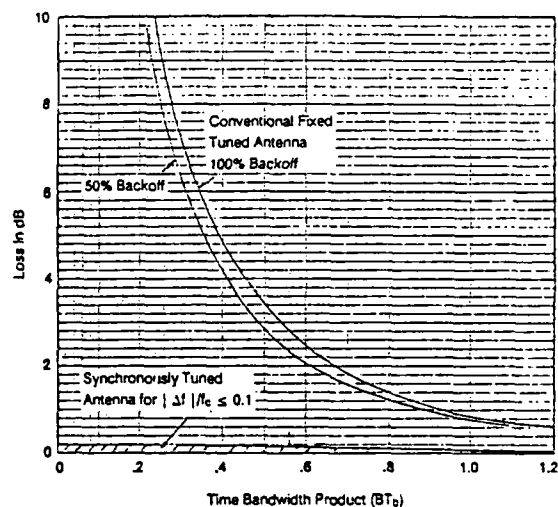


Figure 4. Comparison of Signal Loss for an MSK Modulated Waveform

#### REFERENCES

- [1] H.G. Wolff, "High-Speed Frequency-Shift Keying of LF and VLF Radio Circuits," IRE Trans. Commun. Syst., Vol. CS-5, pp. 29-42, Dec. 1957.
- [2] H.F. Hartley, "Transient Response of Narrow-band Networks to Narrow-band signals with applications to Frequency Shift Keying," IEEE Trans. Commun. Technol., Vol. COM-14, pp. 470-477, Aug. 1966.