Development of models simulating operation of elements of radio devices, for solving problems of ensuring electromagnetic compatibility of radio electronic means

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Abstract. To study the effect of phase-shift signals parameters on EMC of REM, a generalized signal generation model in a radio transmitter was developed which allows obtaining digital representations of phase-shift signals, which are a continuous pulse in the time domain and on the frequency axis with different signal element envelope shapes.

1. Introduction.
In the model using the "Fast Fourier Transform" (FFT) apparatus [1], continuous signal values sample modeling on the time axis is provided with the matched parameter values at the starting and end points.

To simulate the signal generation in a radio transmitter, the following generalized scheme is used:

![Figure 1. The scheme of a phase-shift signal generation model in a radio transmitter sequencing of a signal generated by the modulator through a power amplifier and a band-pass filter at the output of the transmitter is simulated.](image)

2. Methodology.
To obtain the modulation of quadrature phase-shift keying (QPSK) signals, offset quadrature phase-shift keying (OQPSK) signal is represented as independent in-phase and quadrature components by multiplying the in-phase component by \( \cos(\omega_0 t) \), and a quadrature component - by \( \sin(\omega_0 t) \), where \( \omega_0 \) is the carrier signal frequency. In addition, for OQPSK signals, one of the channels’ half elementary signalling period delay is taken into account. This allows one to avoid phase jumps by 180°, but makes phase transitions twice frequent. The scheme of the QPSK and OQPSK signal modulator is represented in figure 2.
Figure 2. The scheme of QPSK and OQPSK signal modulator

The following notation is used in this figure:
P is a channel allocator; BPSK (binary phase-shift keying); \( T/2 \) is the half elementary signalling period delay when generating OQPSK signals.

Figure 3 shows the graphs of complex representation of phase-manipulated signals (BPSK, QPSK, and OQPSK) on the time axis at the video frequency.

Figure 3. The graphs of phase-manipulated signals’ complex representation: a) BPSK; b) QPSK; c) OQPSK.

Since signal element envelope shape \( F(t) \) is one of the most significant factors affecting the spectral characteristics of the signal, and therefore the REM parameters of EMC, the model provides mechanisms for envelope formation of various types. In particular, for BPSK signals of a bell-shaped signal element envelope, the shape of the envelope is given either by a sinusoid or Legendre polynomials [2].

Signal element sinusoidal envelope is given by:

\[
F(t) = U \sin \left( \frac{\pi t}{T} \right).
\]  
(1)

Figure 4 shows a graph of signal, which signal element envelope shape is given by relation (1).

Figure 4. BPSK signal of a sinusoidal-shaped signal element envelope

Using Legendre functions, the signal element envelope is given as follows:

\[
F(t) = U \sin(a_0 P_0(2tT - 1) + a_1 P_1(2tT - 1) + \ldots + a_L P_L(2tT - 1))
\]  
(2)

where \( a_i \) coefficients that determine the shape of the envelope (i=0..L); \( P_i(x) \) is Legendre function to the \( i \) power; \( T \) - elementary signalling period.
Table 1 gives some examples of $a_i$ coefficient values, for BPSK signal element envelope, which is given in the form of relation (2).

**Table 1.** Some examples of $a_i$ coefficient values in the form of relation (2), which give bell-shaped signal element envelope

| $i$ | $a_i$       | $P_i(x)$                  |
|-----|-------------|---------------------------|
| 0   | 0.785398    | 1                         |
| 1   | 0.748528    | $x$                       |
| 3   | -0.070611   | $(5x^2-3x)/2$             |
| 5   | -0.001126   | $(63x^3-70x^2+15x)/8$     |

Figure 5 shows a BPSK signal of a bell-shaped signal element envelope, which is given in the form of relation (2), for the coefficient values according to the data in table 1.

![Figure 5. BPSK signal of a bell-shaped signal element envelope, which is given using Legendre polynomials](image)

For a sequence of rectangular pulses of different polarity, the possibility of sinusoidal smoothing of intersymbol transitions is provided. In this case, within the given element envelope edge (transient period) we use the following mathematical models [3]:

- for rising element envelope edge
  \[
  F(t) = U \sin \left( \pi \frac{t}{T_{fp}} \right), \tag{3}
  \]

- for falling element envelope edge
  \[
  F(t) = U \sin \left( \pi \frac{T - t}{T_{fp}} \right), \tag{4}
  \]

where $T_{fp}$ is the element envelope leading-edge time

It should be noted that the minimum-shift keying (MSK) signals can be generated the same as OQPSK signals with a sinusoidal element envelope, i.e. using relation (1). Figure 6 shows the graphs of MSK signal complex representation on the time axis at zero frequency.

![Figure 6. The graphs of MSK signal complex representation](image)

To study the characteristics of complex digital signals, we have developed the software implementation of the model. The imitation of the coded digital signal generation process is provided. For each information symbol, there is a corresponding signal element code sequence, which length is
equal to the value of bandwidth-duration product. The modulator diagram of such signals is shown in Figure 7.

![Diagram of crossing digital signals]

**Figure 7.** Scheme of crossing digital signals

The power amplifier effect on signal spectral characteristics is counted by modeling the phase change of the output signal on the transmitter amplifying stage, depending on its amplitude. This allows one to take into account the effect of amplitude-phase conversion. Depending on the type of amplifier, various approximating relations are used [4]:

1) for klystron amplifiers

\[
\Delta = \begin{cases} 
(0.4A)_{\text{max}}, & 0 \leq A < 0.2; \\
(1.15A - 0.15)_{\text{max}}, & 0.2 \leq A \leq 1; 
\end{cases}
\]  

(5)

2) for amplifiers on traveling wave tubes

\[
\Delta = \begin{cases} 
(2.15A)_{\text{max}}, & 0 \leq A < 0.0316; \\
\left(-0.04 + 3.55A - 3.77A^2\right)_{\text{max}}, & 0.0316 \leq A < 0.5; \\
(0.4A + 0.6)_{\text{max}}, & 0.5 \leq A \leq 1; 
\end{cases}
\]  

(6)

3) for travelling-wave tube amplifiers with increased linearity

\[
\Delta = \begin{cases} 
(8.86A)_{\text{max}}, & 0 \leq A < 0.0316; \\
\left(1 - 0.97e^{-0.31A}\right)_{\text{max}}, & 0.0316 \leq A < 0.133; \\
\left(1 - 0.7e^{-7A}\right)_{\text{max}}, & 0.133 \leq A \leq 1; 
\end{cases}
\]  

(7)

4) for other cases

\[
\Delta \varphi = A \varphi_{\text{max}}.
\]  

(8)

where \( \Delta \varphi \) is the phase additive of the signal as a result of amplitude-phase conversion;

\( A \) - the square of the normalized signal power.

In addition, for the developed model, it is possible to simulate the use of a nonlinear cut-off mode transmitter of the amplifier, which is used to increase the efficiency of the amplifying path. When using this mode, the high-frequency signal excludes all instantaneous voltage components, which are less than the set value. The set value is equal to \( U \cos(\theta) \), and is determined by the specified cut-off angle \( \theta \). For example, if \( \theta = 90^\circ \), all negative values of the high-frequency signal voltage [5] are eliminated. The restoration of the truncated signal carrier is carried out as a result of passing through the output band-pass filter of the receiver.

The Butterworth filters of different orders are considered as band-pass filters for phase-manipulated signals’ generation model. The amplitude-frequency and phase-frequency characteristics of the transmission coefficients are calculated using the following approximating relations [6]:
\[ K(f_i) = \frac{1}{\sqrt{1 + (f_i)^2}}, \quad (9) \]

\[ \phi(f_i) = \frac{1}{2} \sum_{i=1}^{n} \left\{ \arctg \frac{f_i + \cos \left( \frac{\pi(2k-1)}{2n} \right)}{\sin \left( \frac{\pi(2k-1)}{2n} \right)} + \arctg \frac{f_i - \cos \left( \frac{\pi(2k-1)}{2n} \right)}{\sin \left( \frac{\pi(2k-1)}{2n} \right)} \right\}, \quad (10) \]

where \( K \) is the transmission coefficient;

\( \omega \) is the transmission coefficient phase, which determines the value of the quadratic factor;

\( f_i \) is relative frequency \( f_i = \left( i - 1 \right) \Delta F / F \), where \( i = 1 \ldots N \);

\( \Delta F \) is the frequency sampling increment;

\( F \) is half the filter bandwidth by the level of -3 dB;

\( N \) is half the array length for FFT.

The parameters of the filter bandwidth by the level of -3 dB and its order determines the value of the quadratic factor.

3. Conclusion.

Thus, the developed phase-shift signal generation model allows one to simulate the generation process of simple and complex BPSK and QPSK signals with different signal element envelope shapes, as well as MSK signals, taking into account the band-pass filtering distortion effects and the amplitude-phase conversion effect of the transmitter amplifier.

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