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Wideband Signal Generation for Jamming Radio-Controlled Improvised Explosive Devices

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Abstract— **This paper focuses on modelling operation of a wideband jamming signal generator, considering the effects present in real device which influence the shape of transmitted signal's spectrum. Introduction is followed by a brief overview of AEGIS project, aim of which is to develop a mobile generator of electromagnetic curtain. Next, simulation model is described which includes the factors determining the form of the signal at the output of real generator. Selected simulation results for specific configuration of generator are shown as well**.

***Keywords*—electronic warfare, IED, jamming, RCIED, wideband generator.**

I. Introduction

One of fundamental aspects of countering terrorist activities is effective detection and neutralization of so called IEDs (improvised explosive devices). Such devices are mainly used in areas of the world which are notorious for asymmetric conflicts, such as some middle-east countries. However, IEDs may be used as well as a means of terrorist attack aimed at civilians anywhere in the world. Specific group of IEDs are the ones where detonation is triggered by radio signals. They are termed RCIED (Radio-controlled IED). They usually make use of universally available wireless transceivers taken from consumer electronics, such as mobile phones, toys, remote controllers, etc.

Preventing RCIED from being detonated may be accomplished by generating high-power jamming signals which disable reception of triggering signals. This is sometimes referred to as electromagnetic (EM) curtain. Effective jamming requires power of interference at receiver RF input to be considerably higher than power of useful signal. As a consequence of this fact, the surface area where RCIEDs are disabled strongly depends on following factors: jammer's transmitted power, transmit antenna pattern, receiver sensitivity, landform, environment (e.g. urban, rural) and others.

Because of the fact that exact frequency band of signal initiating the detonation is most often not known, jamming needs to cover frequency range as wide as possible. This is one of the major challenges for developing an effective generator of EM curtain. What is more, the curtain must not jam own communication links used by forces which take part in counter-terrorist, military or emergency operation. Thus, it is required that EM curtain generator offers possibility to arbitrarily define protected frequency bands, inside which the power of interference will be drastically reduced.

This paper is related to modelling and simulating operation of a wideband jamming signal generator, considering hardware-related effects which have influence on the resulting shape of transmitted signal spectrum. Next section of the paper presents the outline of AEGIS project, aimed at developing an effective mobile generator of EM curtain. In the third section, model of wideband signal generator is described, which takes account of factors causing signal distortions in path from digital-to-analog converter (DAC) to transmit antenna. Finally, example simulation results are shown presenting performance evaluation of particular wideband jammer.

II. AEGIS Project

Modern mobile EM curtain generator is currently developed in Gdansk University of Technology within a project called AEGIS. Aim of this project is to build a device which will provide reliable protection from threats originating from RCIEDs, detonation of which is triggered via public cellular networks. Dimensions of this device will be similar to the size of a suitcase. It will be equipped with quick-assembly antenna set. Remote control of the device will be possible using wire connection. Mobility of the device will be provided by mounting it on a self-propelled, remotely controlled platform. The main advantage of AEGIS over commercially available jammers [1], is that it will allow to define protected frequency bands fully arbitrarily, without any hardware modifications.

One of the first tasks in the project is to design proper algorithms for generating wideband waveforms which will produce signals of desired spectrum shape. There are two main constraints put on these algorithms, stating that they should:

- provide highest possible transmit power of undistorted jamming signal in order to maximize effective range of jamming,
- provide high attenuation of jamming signal in protected frequency bands.

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Evaluation of different wideband waveform generation algorithms for jamming purposes requires comparing specific parameters of transmitted signals. Values of these parameters, in given conditions, may be estimated through simulations which are further described in the remainder of this paper.

III. Model of Wideband Signal Generator

Generating wideband jamming signal begins with creating its baseband equivalent waveform in digital domain. Digital processing is necessary to obtain a signal of desired spectrum shape, considering the fact that number and ranges of protected frequency bands are arbitrary. In-phase and quadrature (I and Q) components of complex digital waveform are converted to analog domain and fed into quadrature modulator which shifts signal frequency to a desired RF band. Adequate signal strength of transmitted signal is provided by power amplifier, which is located directly before transmit antenna. Block scheme, representing the model of EM curtain generator, is shown in Fig. 1.

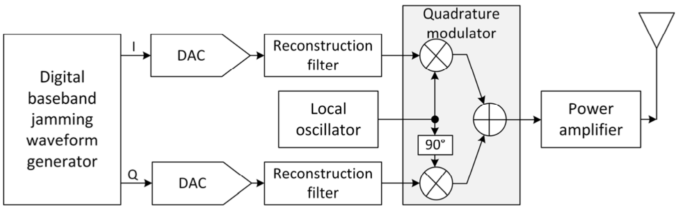

Fig. 1. Model of wideband jamming signal generator

Final form of transmitted signal depends not only on waveform generation method and given ranges of jammed and protected frequency bands. It is also determined by physical properties of analog hardware parts. Because of inherent imperfections present in electrical components, eventual signal spectrum shape may be noticeably different than initial spectrum of digital waveform [2]. Thus, conducting reliable evaluation of wideband waveform generation algorithms requires all significant factors affecting shape of signal spectrum to be included in simulation model.

Considering order of signal processing operations in generator path, the first effect causing spectrum distortions is quantization nose, resulting from limited DAC resolution. Precision of waveform samples must be reduced to match DAC capabilities, which results in increase of overall noise floor. Thus, number of bits per sample at DAC input determines maximum achievable ratio of average power spectral densities between jammed and protected frequency bands. This parameter from this point will be referred to as JPR (Jammed-to-Protected power density Ratio).

Additional negative effect on spectrum shape is induced by non-zero DC component on the outputs of DACs. It results in presence of undesired peak at 0Hz in baseband spectrum, which eventually occurs at carrier frequency of transmitted signal. Such peak, when located in protected frequency band, will cause interference which may lead to disabling wireless channel for own communications.

Next DAC-related factor influencing signal spectrum shape is the width of pulse corresponding to each waveform sample. Ideal digital-to-analog converter outputs series of infinitely short pulses – Dirac deltas:

$$s_{DAC}(t) = \sum_{n=-\infty}^{\infty} s[n] \cdot \delta(t - nT), \tag{1}$$

where $s[n]$ is n-th DAC input sample, T is sampling period and $s_{DAC}(t)$ is value of DAC output signal at instant t.

Assuming that real DAC follows the zero-order-hold model, it generates sequences of rectangular pulses of width equal to sampling period and amplitude corresponding to sample value. Real DAC output signal is represented by convolution of ideal DAC output signal with rectangular time-domain window function

$$\hat{s}_{DAC}(t) = s_{DAC}(t) * \Pi\left(t - \frac{T}{2}\right), \tag{2}$$

where hat symbol denotes output from real DAC. In frequency domain, the above convolution corresponds to a multiplication of ideal DAC output spectrum with a |sin(x)/x|-shaped function taking zero values for arguments equal to integer multiples of sampling frequency [3]. This means that shape of magnitude spectrum of generated signal is changed. If magnitude spectrum of digital waveform at DAC input is flat, frequency components of corresponding DAC output signal spectrum tend to decrease while approaching Nyquist frequency [4]. This distortion may be compensated with digital or analog filter of frequency response being the reciprocal of real DAC frequency response.

Analog signal from DAC output is passed through a low-pass reconstruction filter which removes all frequency components located above Nyquist frequency. Spectrum at filter output is a multiplication of input signal spectrum and filter frequency response. This means that all pass-band ripples and filter roll-off factor will be reflected in spectrum of transmitted signal.

Another block of generator which influences the shape of signal is the quadrature modulator. Apart from shifting signal frequency components from baseband to RF band, it may introduce additional distortions to signal spectrum. Two main sources of modulator-related distortions may be identified. One of them is phase noise of local oscillator (LO) which generates carrier frequency. Similarly to quantization noise, phase noise causes undesired increase of signal power spectral density inside protected frequency bands.

Second source of distortions in signal at modulator output are amplitude imbalance and phase impairment between modulator branches. This means that LO signal in in-phase (I) branch has different amplitude than respective signal in quadrature (Q) branch and that relative phase shift between these signals is not exactly 90 degrees. Because of this, unwanted mirror image components occur in complex spectrum of modulated signal. These images cause side band spurs in spectrum of real signal at modulator output [5]. In turn, it has negative impact on obtained JPR values.

Spectrum distortions are also introduced when signal level is boosted in power amplifier. They are a consequence of non-linearity in amplifier gain characteristics, which results in occurrence of higher order harmonic components and intermodulation products. Amplifier simulation model is defined by its gain curve, which is assumed to be linear in active region and flat in saturation region. In transition region gain curve passes through 1 dB compression point and is calculated using polynomial interpolation between active and saturation lines.

Although it is planned to use linear power amplifiers in AEGIS project, the simulation model takes account of nonlinearities related to gain compression. It is expected that amplifier will be driven close to saturation region in order to achieve highest possible output power. Maximizing signal power at amplifier output, considering acceptable level of distortion, requires that signal at amplifier input has low PAPR (peak-to-average power ratio). Value of this parameter may vary relevantly for different algorithms of signal waveform generation. PAPR and JPR are two main parameters which are considered in evaluation and comparison of wideband jamming waveform generation algorithms.

IV. Simulation of Jamming Signal Generation

In this section, simulation results are presented for given jamming scenario. It was assumed that jamming signal has bandwidth of 500 MHz and complex waveform is sampled at 550 MHz Five protected frequency bands were defined in baseband with center frequencies of: -100 MHz, -50 MHz, 0 Hz, 130 MHz and 200 MHz, with respective bandwidths: 20 MHz, 10 MHz , 100 kHz, 100 kHz and 10 MHz. Jamming signal waveform was created by prior generating magnitude spectrum of desired shape, which is flat in jammed bands and excised in protected bands. Next, inverse fast Fourier transform (IFFT) was applied to this spectrum to obtain time-domain representation. Resulting waveform was additionally filtered in low-pass FIR filter to limit its frequency range to ±250 MHz. Power spectrum of baseband waveform is shown in Fig. 2.

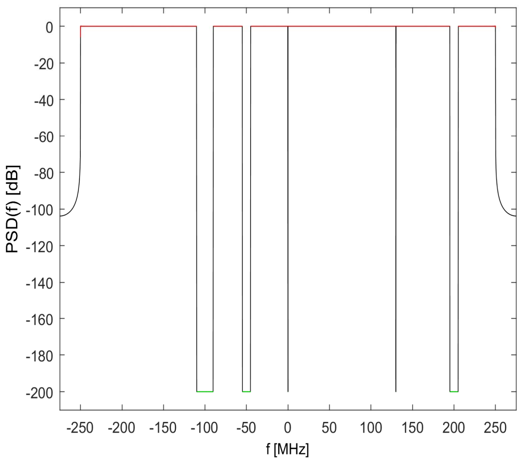

Fig. 2. Normalized power spectrum of baseband waveform

In order to obtain waveforms representing I and Q baseband signal components at DAC outputs, oversampling was applied, where each sample of original waveform was repeated ten times. Oversampling was preceded by quantization which reduced samples' resolution from 64 bits to 12 bits – one of typical values for high speed DACs. DC offsets at DAC outputs were added, equal to -0.02% and 0.01% of nominal I and Q component amplitudes.

In modulation process, signal frequency was shifted from baseband to RF band with center frequency of 1 GHz. Power spectral density of LO phase noise at frequency offsets of 1 kHz, 10 kHz, 100 kHz, 1 MHz and 10 MHz was assumed to be -84 dBc/Hz, -100 dBc/Hz, -96 dBc/Hz, -109 dBc/Hz and -122 dBc/Hz respectively. Spectrum of signal at LO output is presented in Fig. 3.

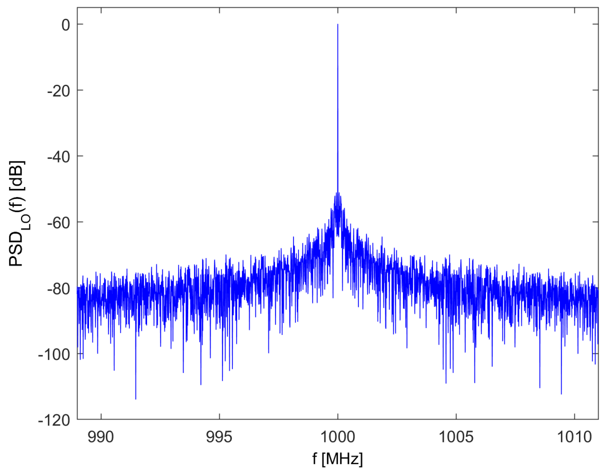

Fig. 3. Power spectrum of signal generated by local oscillator

Angular shift representing I/Q phase impairment was set to -0.2°. Amplitude imbalance was equal to 0.05 dB, where positive value means higher amplitude in Q branch. These are actual values taken from datasheet of ADL5386 quadrature modulator chip [6].

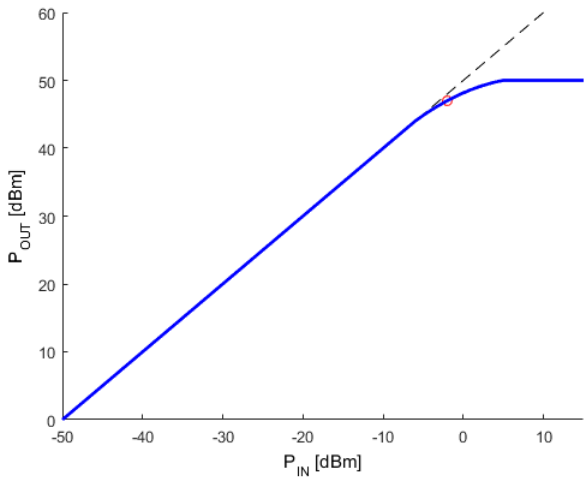

Fig. 4. Power amplifier model gain curve

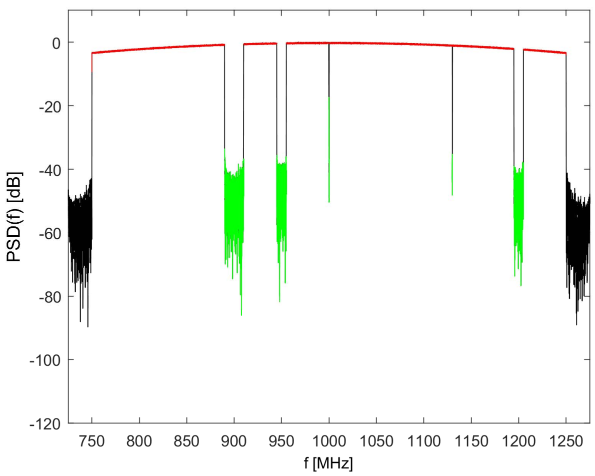

Fig. 5. Normalized power spectrum of transmitted jamming signal

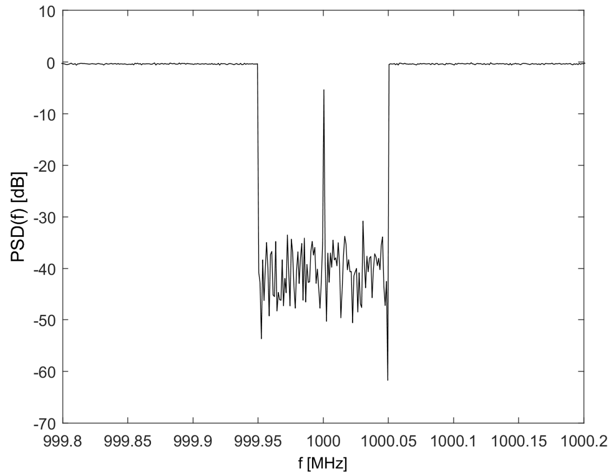

Fig. 6. Power spectrum in the vicinity of center frequency

Waveform corresponding to modulated signal was then processed in a simulator block which implements operation of a power amplifier. Gain curve for this block was evaluated basing on parameters of commercially available wideband amplifier [7]. It offers 50 dB gain in active region 100 W absolute maximum output power and 50 W output power in 1 dB compression point. Gain curve was plotted in Fig. 4. and 1 dB compression point was marked with red circle.

Resulting power spectrum of signal at power amplifier output was presented in Fig. 5. It may be seen that power spectral density of jamming signal gradually decreases while moving away from center frequency. It is a consequence of real DAC operation limitations described in section III. Moreover, power spectral density in protected frequency bands is significantly higher than in case of baseband waveform (see Fig. 2.). This increase of spectrum floor is caused by combined effects of quantization noise, LO phase noise and I/Q impairments in quadrature modulator.

Result values of Jammed-to-Protected power density ratio are presented in table I. Two scenarios were considered. In first of them, peak power of signal at amplifier input did not exceed 1 dB compression level which was 0 dB (P_{IN} + $PAPR_{IN}$ = -15 dBm + 13.4 dB = -1.6 dBm). In the second case, peak power exceeded 1 dB compression point (P_{IN} + $PAPR_{IN}$ = -10 dBm + 13.4 dB = 3.4 dBm), which means that during some time intervals amplifier was driven to operate in saturation region. This introduced signal distortions causing significant decrease of JPR values in protected frequency bands.

TABLE I. JAMMED-TO-PROTECTED POWER DENSITY RATIOS

$PAPR_{IN}$ = 13.4 dB, $P_{IN@1dB\ compression}$ = 0 dBm		
Protected freq. band	***JPR (P_{IN} = -15 dBm)***	***JPR (P_{IN} = -10 dBm)***
900±10 MHz	45.2 dB	35.0 dB
950±5 MHz	43.6 dB	34.3 dB
1000±0.05 MHz	24.9 dB	25.2 dB
1130±0.05 MHz	36.7 dB	35.4 dB
1200±5 MHz	45.4 dB	35.6 dB

As may be seen, achievable JPR values for narrow protected bands (100 kHz bandwidth) is much smaller than for wide ones. This is mainly caused by influence of LO phase noise which causes signal power leakage to protected frequency bands from adjacent jammed bands. For wider protected bands, the impact of LO phase noise on overall noise floor is lower as LO power spectral density decreases with frequency offset (as shown in Fig. 3). In case of third protected band, located in the center of 500 MHz-wide jamming signal band, JPR is mostly determined by presence of additional spectrum peak, caused by non-zero DC component in I and Q branches. Zoomed-in view of central part of spectrum from Fig. 5. was shown in Fig. 6. Interfering harmonic component is clearly visible.

V. CONCLUSION

Simulations basing on presented model may be used for rough estimation of Jammed-to-Protected power Ratio values. Various jamming waveform generation methods may be compared using this generator model to evaluate which one provides acceptably low PAPR and high JPR values. Best-performing algorithm will be implemented in EM curtain generator. When the prototype of AEGIS device is ready, simulation results are going to be verified experimentally.

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